Vertical Excursions Breathing Air from Nitrogen-Oxygen or Air Saturation Exposures

Rockville, Md.
May 1976

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration

Vertical Excursions Breathing Air from Nitrogen-Oxygen or Air Saturation Exposures

By:

James W. Miller, Editor
George M. Adams
Peter B. Bennett
Richard E. Clarke
Robert W. Hamilton, Jr.
David J. Kenyon
Robert I. Wicklund

Rockville, Md.
May 1976

U.S. DEPARTMENT OF COMMERCE
Elliot L. Richardson, Secretary

National Oceanic and Atmospheric Administration
Robert M. White, Administrator

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402.
Price $1.85

CONTENTS

ACKNOWLEDGEMENTS

In 1974 the authors of this report met to discuss the status of air and nitrogen/oxygen saturation excursion diving. Although several projects had been completed and more were being planned, it became clear that the results of neither laboratory nor open-sea experiments had been adequately integrated and documented. It was decided therefore to compile the available results relating to air excursion diving into a single document.

Special appreciation is expressed by the authors to the following persons for suggestions made or for providing information on specific projects not otherwise available: To Mr. Mark Freitag, Strongwork Diving (International) Ltd. and Cdr. Claude Harvey, Naval Submarine Medical Research Laboratory, for suggestions during the initial discussions; and to Lt. Cdr. Antonio de Lara, Centro de Buceo de la Armada, Cartagena, Spain, for information on the TONOFOND experiments. Appreciation also is extended to Dr. Richard B. Philp, University of Western Ontario, for providing information on the hematology and blood chemistry studies which were part of the SCORE and Hydro-Lab programs. The outstanding job performed, over and above their regular duties, by Mrs. Marilyn Trimble and Miss Rebecca Milton of the Office of Naval Research, London, in typing the manuscript also is gratefully acknowledged.

AUTHOR'S AFFILIATIONS

James W. Miller
Deputy Director
Manned Undersea Science and Technology
National Oceanic and Atmospheric Administration
Rockville, Maryland
(Temporarily assigned to the Office of Naval Research,
London, England)

George N. Adams
810 Egan
P.O. Box 201
Denton, Texas
(Formerly Submarine Medical Research Laboratory,
New London, Connecticut)

Peter B. Bennett
Department of Anesthesiology
Co-Director, F. G. Hall Laboratory for Environmental Research
Duke University Medical Center
Durham, North Carolina

Richard E. Clarke
Commercial Diving Center
272 Flies Avenue
Wilmington, California
(Formerly Deputy Director for Hydro-Lab Program
Perry Oceanographic Foundation
Freeport, Grand Bahamas)

Robert W. Hamilton, Jr.
Vice President and Director of Research and Operations
Tarrytown Labs, Ltd.
Tarrytown, New York

David J. Kenyon
Vice President
Tarrytown Labs, Ltd.
Tarrytown, New York

Robert I. Wicklund
Special Council to the Senate
Office of Senator Lowell P. Weicker
Washington, D.C.
(Formerly Project Director for Hydro-Lab Program
Perry Oceanographic Foundation
Freeport, Grand Bahamas)

LIST OF TABLES

LIST OF TABLES (CONT.)

LIST OF FIGURES

LIST OF FIGURES (CONT.)

I. INTRODUCTION

The number of individuals involved in diving related activities has been increasing steadily for the past several years. This increase is reflected in scientific diving as well as in recreational and commercial diving. Because of this heightened interest, which is further accentuated by national energy requirements, there is a need for equipment and procedures that will allow the diver to operate with greater flexibility, safety, and effectiveness. While significant achievements are being made towards working at great depths, particularly in the offshore industries, much work will continue to be performed in relatively shallow water; i.e., less than 300 feet.

For both scientific and working purposes, the need for extended diving times is becoming more apparent. Further, increased costs dictate that the most economical procedures be used consistent with safety and availability of breathing gases and that sophisticated systems and exotic breathing gases be used only when absolutely necessary. In addition to extending diving times, it must be assured that divers have maximum flexibility with regard to carrying out horizontal and vertical excursions. While mobility has been aided significantly by the use of various swimmer propulsion systems and is primarily an engineering problem, the extension of diving times requires additional basic and applied physiological research. Most investigations to date, relating to vertical excursions, have used the surface (one atmosphere) as the basis for downward excursions. There are decompression dive tables, no-decompression dive tables, repetitive dive tables, etc., all based on being saturated on air at the surface. There is now a need for similar data using higher ambient pressures as a point of departure (or storage depth).

Because of the above factors, a renewed interest in air and nitrogen-oxygen saturation diving has occurred during the past 3-4 years.[1] Recent investigations have shown that it is possible to use air and nitrogen-oxygen breathing mixtures in situations which heretofore were thought to require the use of more exotic breathing gases.

This monograph has been prepared to document the state-of-the-art of hyperbaric saturation exposures employing air or nitrogen-oxygen breathing mixtures. Emphasis is placed on the use of vertical excursions during saturation exposures. Laboratory and field projects which have application in the fields of diving and tunneling are described. Programs discussed in detail are those

---

[1]Saturation diving is a condition in which the duration of an exposure to an inert gas at a fixed high pressure has approximated the time required for all tissues of the body to absorb all the gas they can, such that no appreciable additional gas can be dissolved in the tissues regardless of the duration of further exposure. Once a diver has achieved that state (saturation), the required time for decompression is the same regardless of the total duration of the exposure.

carried out primarily to study vertical excursion profiles or those in which operational protocol required significant vertical excursions to be made. No attempt is made to present detailed analyses of each individual project. Rather, significant results, their application, and excursion profiles successfully employed, are discussed. Current capabilities are assessed and problem areas requiring additional investigation identified.

II. HISTORY

Pioneering experiments beginning in the 1930's indicated that saturation diving might be feasible (Behnke 1969). Modern saturation diving had its beginnings in 1958, when Captain George Bond, M.C., U.S.N., suggested that blood and tissue absorb as much inert gas as it is capable of holding within approximately 24 hours. After some preliminary animal experiments to depths of 200 fsw (Workman, Bond and Mazzone 1962), human experiments were conducted at the Naval Medical Research Laboratory, New London, Connecticut, in 1962-63. These chamber studies were climaxed by a 12-day exposure to a simulated depth of 222 fsw, using a breathing mixture of 92 percent helium, 5 percent nitrogen, and 3 percent oxygen (Bond 1964).

These initial studies paved the way for a series of investigations over the past 10 years in which animals and humans have been exposed to pressures as deep as 4,000 and 2,000 fsw respectively, under both saturated and nonsaturated conditions. Although the deep investigations have not as yet been followed up by routine open-sea operations, commercial divers are now working at depths of 600-800 feet with the expectancy of going beyond 1,000 feet within the next year. While the capability to operate at such depths is essential for the recovery of fossil fuels and minerals, for rescue efforts, and for occasional salvage, most diving is still done at depths of less than 250 feet.

Since 1962, several laboratory and open-sea programs have been carried out in which significant vertical excursions were made from saturation storage depths exceeding one atmosphere. Only those programs in which the breathing gas used was air or nitrogen-oxygen will be discussed in this monograph. Figure 1 summarizes these programs by showing the breathing gas used, the saturation depths, and the maximum vertical excursion depths and times[2].

---

[2]In Fig. 1, the circles indicate the saturation depth and the letters 'A' and 'N' next to the circles designate whether the storage breathing gas used was air (A) or a mixture of nitrogen/oxygen (N). The short horizontal bar at the top and bottom of the vertical line indicates the depth of the maximum excursion. The number by the bar is the "bottom" time of the maximum excursion. The data shown for Tektite I and II represent laboratory experiments. In the Tektite open-sea programs the saturation depth was 42 fsw for both programs. Vertical excursions were made to a depth of 20 feet above storage depth for no longer than one hour, and below storage depth to 80 fsw for periods up to one hour.

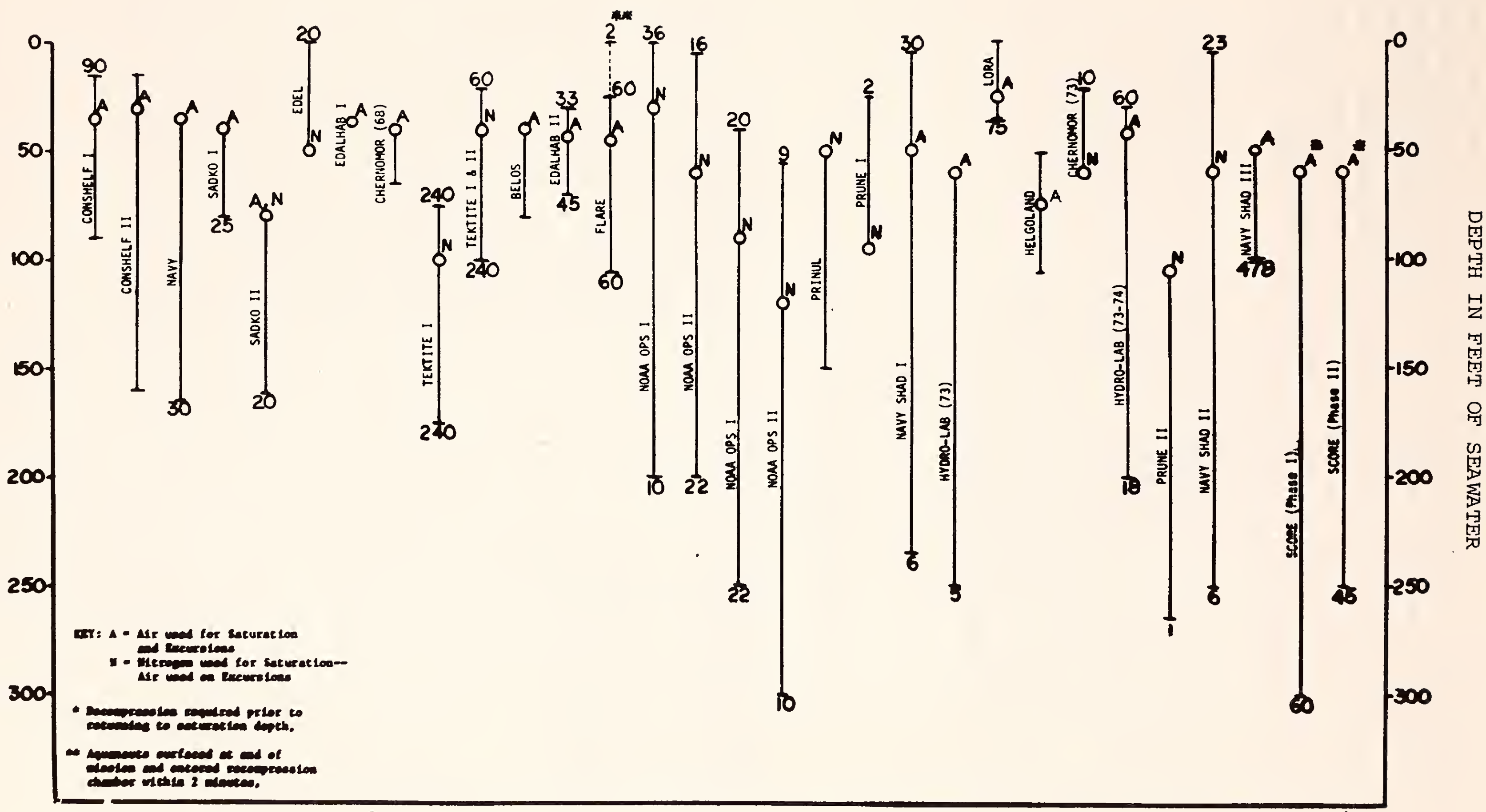

Fig. 1. Vertical excursions and maximum times to depths of 300 fsw, 1962 to 1975.

The shallowest air saturation depth to date is the 26-foot program of LORA (English, 1973). The most significant feature of the LORA program is the fact that both aquanauts safely surfaced with no decompression after spending 24 hours at a depth of 26 fsw (which included four excursions to 35 fsw). Further details of this program are discussed later. The deepest saturation on nitrogen-oxygen is 120 fsw, which was achieved in the NOAA-OPS program. During this program, the subjects made upward excursions to a depth of five fsw and downward excursions to a depth of 300 fsw. This program also is described in detail later.

Larson and Mazzone (1967) reported on the first program designed specifically to study vertical excursions from air saturation. Following a series of dry chamber studies using dogs, a similar series of studies was conducted using 13 human subjects. Air was breathed both during the saturation and excursions. The saturation depth was 35 fsw, with excursions as deep as 165 fsw. With one exception, only a single excursion was made by each pair of subjects following a 24-hour period of saturation at 35 fsw. Table 1 shows the excursion times and decompression profiles. Table 2 shows the results of the human and animal excursion series.

TABLE 1

Excursion times and decompression profiles*

Depth and Bottom Time of Excursion	Decompression to Surface
165 ft for 30 min 135 ft for 60 min 117 ft for 90 min 100 ft for 120 min	Ascent to 10 ft at 5 fpm 2 hrs on air at 10 ft 1 hr on O_2 at 10 ft Ascent to surface at 2 fpm
105 ft for 150 min	Ascent to 20 ft at 3 fpm 20 min on air at 20 ft Ascent to 10 ft at 2 fpm 2 hrs on air at 10 ft 1 hr on O_2 at 10 ft Ascent to surface at 2 fpm
100 ft for 240 min	Ascent to 20 ft at 3 fpm 40 min on air at 20 ft Ascent to 10 ft at 2 fpm 2 hrs on air at 10 ft 1 hr on O_2 at 10 ft Ascent to surface at 2 fpm

*(Larson and Mazzone, 1967)

TABLE 2

Description and results of animal and human excursion series*

A. Animal Series		B. Human Series	
Saturation exposures	7	Saturation exposures	15
Excursions		Excursions	
165/30	13	165/30	6
135/60	8	135/60	4
117/90	4	117/90	1
109/120	4	109/120	2
105/150	4	105/150	2
100/240	3	100/240	2
Total	36	Total	17
Cases of decompression sickness	0	Cases of decompression sickness	0

*(Larson and Mazzone, 1967)

Larson and Mazzone constructed a no-decompression curve for downward excursion dives from saturation at 35 fsw (Table 3). It was their opinion that the total absence of bends during the study suggests that these data "may err on the conservative side."

The excursion times calculated and tested during NOAA OPS (Hamilton, Kenyon, Frietag and Schreiner 1973) for a depth of 35 fsw are also shown in Table 3 for comparison. (The NOAA OPS program will subsequently be described in detail.) It is seen that the excursion times tested during NOAA OPS are considerably shorter than those tested by Larson and Mazzone.

A study was conducted for the Tektite I program to determine the safe surface interval between direct surfacing from a 42-foot saturation depth (on a normoxic breathing mixture) and the onset of decompression sickness (Edel 1970). This experiment also was designed to develop treatment tables to be used in the event of bends following accidental surfacing.

Six subjects were saturated in a normoxic atmosphere at 42 fsw. All six were decompressed to the surface in one minute. Two subjects each remained at the surface for 10, 15 and 20 minutes prior to recompression to 42 fsw. No symptoms were noted for the 10 or 15 minute groups. One subject in the 20-minute group developed serious neurocirculatory symptoms after 19 minutes, which dissipated rapidly upon recompression to 60 fsw. Based on these experiments, "a surface interval of 15 minutes after accidental surfacing before

recompression to 60 feet, was accepted as safe against the liability of dysbarism" (Beckman and Smith 1972).

TABLE 3

Allowable bottom times (min) for various depths

Depth (Feet)	From Surface (U.S. Navy)	From 35 Feet (Larson and Mazzone)	From 35 Feet (NOAA OPS)
165	5	30	25
135	10	60	46
117	17	90	--
109	20	120	--
105	22	150	108
100	25	240	143

Table 4 was developed during the Tektite I program for treatment of accidentally surfaced divers and for use as an emergency post-saturation decompression schedule beginning at the 40 fsw stop. During the open-sea phases of Tektite I and II, support divers were trained to retrieve a surfaced aquanaut and recompress him within 2-3 minutes, which was well within the recommended safe surface interval.

The limits for excursions to 25 and 100 fsw breathing air used during the 42-foot Tektite program were four hours. While several upward excursions to 25 feet were made, the seafloor topography did not permit downward excursions beyond a depth of 65 feet.

The Tektite II program also included laboratory studies of vertical excursions from a normoxic (94.8 percent N_2 and 5.2 percent O_2) saturation at 100 fsw (Edel, 1970). Two subjects each were used in ascending and descending excursion experiments. In the downward excursion tests, the subjects spent six hours at 175 fsw breathing air, followed by a three-minute ascent to 103 fsw with no symptoms of bends noted.

In the upward excursion tests, the subjects ascended from 100 fsw to 70 fsw. One subject spent eight hours at 70 fsw breathing air; four hours doing weight lifting exercises, followed by four hours of rest. The other subject spent four hours at 70 fsw breathing N_2-O_2 while performing physical exercise.

TABLE 4

Tektite I and II treatment and emergency decompression schedule for use in 50-foot missions (saturation depth 42 fsw)

Depth (fsw)	Time	Total decompression time	Breathing media
60	20	20	Oxygen
↓	5	25	Oxygen
55	20	45	Air
↓	5	50	Air
50	20	70	Oxygen
↓	5	75	Oxygen
45	20	95	Air
↓	5	100	Air
40	20	120	Oxygen
↓	15	135	Air
25	60	195	Air
↓	5	200	Air
20	90	290	Air
20	30	320	Oxygen
↓	5	325	Oxygen
15	90	415	Air
15	60	475	Oxygen
↓	5	480	Air
10	120	600	Air
10	60	660	Oxygen
↓	5	665	Oxygen
5	150	815	Air
5	60	875	Oxygen
↓	5	880	Air
Surface			

Total decompression time: 880 min, or 14 hr and 40 min.
Total 100% oxygen inhalation: 4 hr and 50 min.

Both subjects returned to a depth of 103 fsw without incident. Based on these studies, the Tektite Medical Board agreed to allow upward excursions from 100 fsw to 75 fsw for four hours, and downward excursions to 175 fsw for four hours, with a 12-hour interval between any descending excursion and an ascent to 75 fsw (Beckman and Smith 1972).

In 1972, the FLARE (Florida Aquanaut Research Expedition) program was conducted off the southeast coast of Florida). Twenty-five marine scientists in teams of three, saturated for five days on the seafloor at depths ranging from 42-45 feet. The overall operation is depicted in Fig. 2.

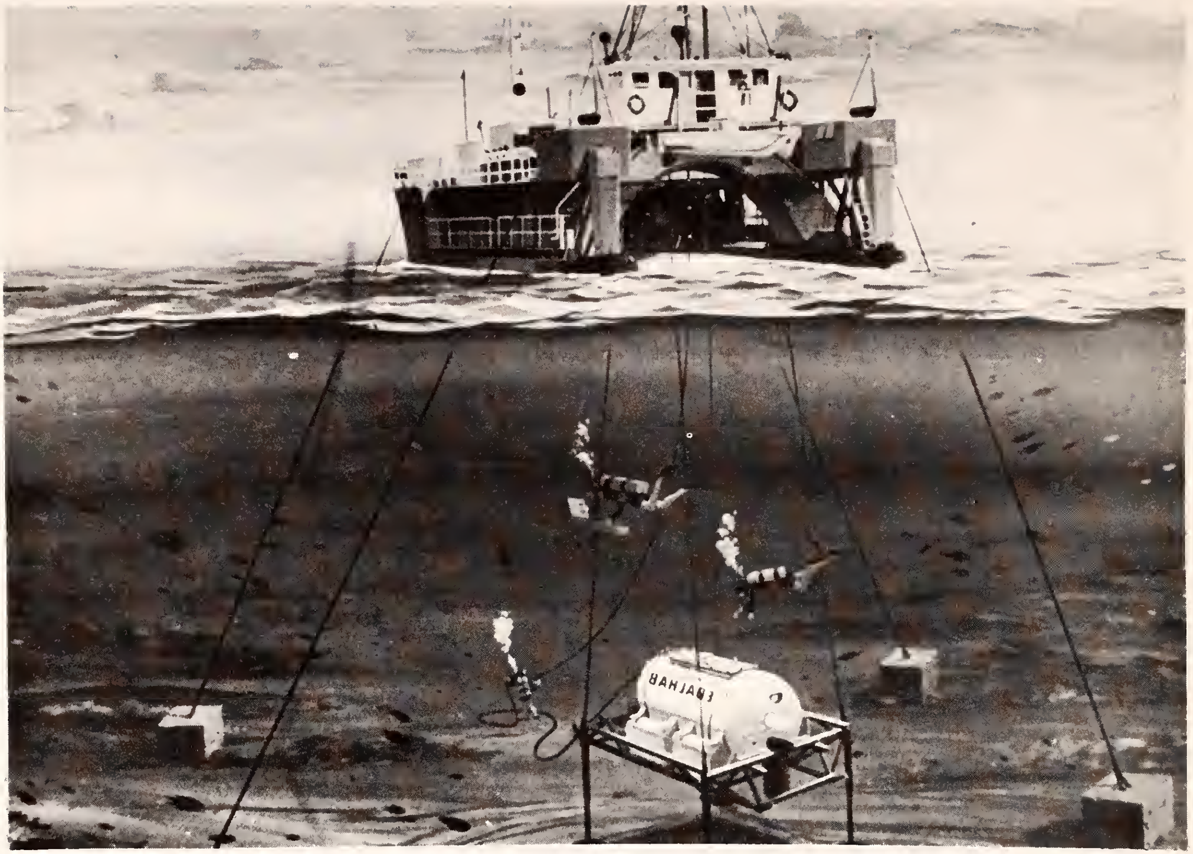

Fig. 2. Artist's conception of project FLARE.

Vertical excursions were carried out as follows: upward excursions were limited to 20 fsw. No-decompression schedules were established for downward excursions by modifying the US Navy Standard Air Table I-II, No-decompression limits, and repetitive group designation table for "No-decompression" dives, see Table 5. Table 5 was used in accordance with directions given in the US Navy Diving Manual for Tables 1-11, 1-12, and 1-13 with the exception that the surface interval noted in Table 1-12 is considered the interval taken in the habitat. Further, when following a descending excursion by an ascending excursion the diver had to be in repetitive group E or lower to go to 30 fsw and in group B or lower to go to 20 fsw. Aquanauts were instructed to plan their daily diving schedules in order to make any anticipated ascending excursions prior to a descending excursion.

The most notable aspect of the FLARE program relating to vertical excursions was the manner in which decompression was achieved. Because the habitat Edalhab was not a pressure vessel, the aquanauts were required to utilize the small decompression chamber located on the deck of the support ship LULU. The procedure called for the aquanauts (one at a time) to ascend from the habitat to the surface next to the support ship. The support crew assisted the aquanaut up the ladder and into the waiting double-lock deck decompression

TABLE 5

No decompression limits and repetitive group designations for downward vertical excursions from a saturated depth of 35 to 45 fsw

Depth From Surface (ft)	Limit of Time at Depth (min)	Repetitive Group														
		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
60	300	60	120	200	300	—	—	—	—	—	—	—	—	—	—	—
65	300	30	60	100	150	200	300	—	—	—	—	—	—	—	—	—
70	300	20	40	60	90	120	150	200	300	—	—	—	—	—	—	—
75	300	15	30	40	60	90	110	145	180	200	300	—	—	—	—	—
80	300	10	20	30	50	60	80	100	120	150	180	200	300	—	—	—
85	300	5	10	20	30	40	50	70	90	100	120	140	180	200	240	300
90	180	5	10	20	25	30	40	50	70	90	100	110	130	150	180	—
100	90	—	5	10	20	25	30	40	50	60	70	80	90	—	—	—
120	40	—	—	5	10	15	20	25	30	35	40	—	—	—	—	—
140	25	—	—	—	5	10	15	20	25	—	—	—	—	—	—	—
160	10	—	—	—	—	—	5	10	—	—	—	—	—	—	—	—

chamber. Once the first aquanaut was safely inside and recompressed to the saturation depth, the procedure was repeated with the other aquanauts. This entire procedure had been rehearsed until the elapsed time between the aquanaut leaving the seafloor and being recompressed in the chamber was only two minutes. This was well within the 15-minute safe surface interval determined during the Tektite I program. Decompression was accomplished using the schedule shown in Table 6. This schedule is based upon the one successfully used in the Tektite II program, but was modified in the following manner:

> Because of transient reduction of pressure to sea level during transfer from habitat to deck chamber, a 40-minute period of oxygen breathing was carried out in the habitat just prior to ascent. As an added safety factor, a 30-minute period of oxygen breathing at 50 fsw was carried out in the deck chamber as soon as the last aquanaut was recompressed to saturation depth. Some 30-minute oxygen-breathing periods during decompression were consolidated into 60-minute periods. The decompression stop at five fsw was eliminated. In its place was a 30-minute period of oxygen breathing at 30 fsw, followed by ascent to the surface on oxygen.

The 25 excursions to the surface for decompression as described above were achieved without incident and became routine by the end of the mission, although two bends cases were reported during decompression. The advantages of this procedure with respect to cost, the lack of the need for a diving bell and simplicity are obvious.

A nitrogen-oxygen saturation excursion program has been underway for the past four years in Cartagena, Spain (de Lara 1975). It is being conducted by the Spanish Navy and is referred to as the TONOFOND Experiments. Ten

TABLE 6

Standard decompression schedule for Project FLARE

Elapsed Time (min)	Depth (FSWG)	Duration (min)	Breathing Medium	O_2 Dose (UPTD)	Cum. O_2 Dose (UPTD)	Notes
	Bottom	40	O_2	116	116	In habitat
	↓		Air			Ascent
	Surface		Air			Transfer to DDC
	↓		Air			Recompression in DDC
	Bottom		Air			
0	↓		O_2			Compress 1 F/sec
	50	30	O_2	96	212	
30	↓	---	O_2			Decompress 1 F/sec
	30	120	Air			
150	↓	5	Air			Decompress 1 F/min
155	25	170	Air			
325	25	60	O_2	130	342	
385	↓	5	Air			
390	20	200	Air			
590	↓	5	Air			
595	15	20	Air			
615	15	60	O_2	102	444	
675	15	40	Air			
715	15	60	O_2	102	546	
775	15	20	Air			
795	↓	5	Air			
800	10	30	Air			
830	10	60	O_2	90	636	
890	10	40	Air			
930	10	60	O_2	90	726	
990	10	40	Air			
1030	↓	5	O_2	10	736	
1035	30	30	O_2	71	807	
1065	↓	30	O_2	51	858	
1095	Surface					

18 hr: 15 min

saturation experiments, using three or four subjects each, have been conducted to date. Table 7 summarizes the TONOFOND experience and reveals a remarkable similarity to the allowable excursion times determined by the NOAA OPS program. In several cases the TONOFOND excursions were significantly larger than those allowed by NOAA OPS but, in most cases, the times were comparable. If the results could be adjusted for differences in habitat oxygen, the differences in allowable excursion time would be even less.

No symptoms of decompression sickness were observed following any of the excursions from saturation. Two cases of decompression sickness did occur however, several hours after completing decompression. Both cases responded successfully to treatment. A significant decrease in nitrogen narcosis was observed as compared to exposure to the same depths when diving from the surface.

III. THEORETICAL BASIS FOR EXCURSION DIVING

Most, if not all, theorists in diving physiology accept the concept that an excursion to a deeper depth, when saturated at depths greater than one atmosphere (absolute), can be conducted safely by using a conventional diving table on a "differential" basis. Thus, a diver saturated at 100 fsw could descend to a depth of 180 fsw and remain for the same period of time as he could when diving to 80 fsw from the surface.

It has been demonstrated repeatedly, however, that longer excursion times can be used from saturation than from the surface. Although the underlying mechanism is not clear, the concept has been exploited such that excursion diving from saturation is now a practical, effective tool. A pragmatic approach has been used in the development of this capability (Schreiner and Kelly 1971). Their study formed the computational basis for the NOAA-OPS experiments described in this document. The mathematical "model" used was developed primarily by Schreiner, following the work of Haldane, Workman, and others. The basis for the model is that gas is transported in the body by the blood, which is assumed always to be equilibrated with tissue. This concept is termed a perfusion limited model. According to this model, gas is taken up or given off by the tissues exponentially as a function of the difference in inert gas partial pressure between the lungs and the tissues.

For purposes of decompression theory, the tissues of the body are conceptually divided into compartments which exchange gas at different rates. If during decompression, the release of gas from these tissue "compartments" exceeds a predetermined value, decompression must be stopped for a period of time. The critical set of factors in this approach is the matrix of gas loadings against which the running totals of inert gas partial pressures are compared.

The "matrix" used for the NOAA-OPS computations was derived empirically, by analyzing the gas loading patterns of nearly 200 actual dives during which

TABLE 7

Summary of Spanish TONOFOND experiments

Sat. Depth (ft)	Saturation Conditions: Exp. No.	Duration (Days)	No. of Divers	$\%O_2$	%N	Excur. Depth (ft)	Number of Air Excursions, Bottom Time (min): 30	60	90	120	180	NOAA OPS Excursion Limits
	1	3	3	14	86	130	1					140*
	2	3	3	14	86	130		2		3		140
49	3	5	4	14	86	130		4		4		140
	4	10	4	14	86	130		7		8		140
	5	3	4	12	88	130		1		2	1**	162*
	6	5	4	12	88	130		2		2	2**	162
65						163		2**				44
	7	10	4	12	88	130		4		4	4**	162
						163		2**	2**			44
	8	3	4	10	90	130					1	360*
						163				2		122*
						195		1**				32*
	9	5	4	10	90	163				2		122
81						195	2	2**				32
						227	2**					19
	10	10	4	10	90	163				4		122
						195	2	4**				32
						227	4**					19
						260	2					--

* Actually tested in NOAA OPS
** Times exceeding NOAA OPS

accurate records had been kept. Those gas loadings which did not result in decompression sickness were accepted as safe, while those which produced decompression sickness were considered to be unsafe. Using the computer-generated gas loadings, a manual selection process was employed, such that some judgment was necessary in producing the completed matrix.

The NOAA-OPS project required computation of no-decompression excursions for depths ranging from 30 to 300 fsw. The computations took into account the gas loadings in each tissue compartment at the beginning of an excursion as well as gas uptake and elimination during the excursion. The loadings were compared with the matrix to determine an excursion time which did not violate the gas loadings permitted by the matrix. Since a substantial amount of gas may remain in the slower compartments until the next excursion, and due to a lack of repetitive excursion data, the entire sequence of excursions was planned in advance.

Because operational requirements also include the need for ascending excursions, such calculations were part of the NOAA-OPS program. Although no body of data was available for use in preparing a matrix for ascending excursions, it is known that gas is released slowly enough to allow short upward excursions. Data from surface decompression experience and from a few ascending excursions made during the Tektite I Program were used to form crude curves showing the time/depth range of safe ascent. These data, plus tolerable gas excesses known to be acceptable in the slow compartments, allowed computation of a set of short ascending excursion tables. As with descending excursions, ascents are affected by gas loadings existing at the beginning of the excursion.

It must be kept in mind that while the concepts of tissue compartments and gas loadings imply inviolate principles, and the notion that divers' bodies behave according to man-made equations, this is far from true. For example, the occurrence of asymptomatic bubbles is not considered by the theory. Fortunately, the concepts can be made to work in practice and several hundred excursions have safely been conducted, both in the laboratory and in the open sea. Further work is necessary to understand and expand the theoretical basis for excursion diving in order to improve the effectiveness of the working diver.

IV. LABORATORY STUDIES

Several laboratory (chamber) experiments have been conducted for the purpose of studying air or nitrogen/oxygen saturation diving, involving extensive vertical excursions. In some programs, the laboratory experiments were designed specifically as a pre-cursor to open-sea studies, while in others no immediate field program was anticipated. This section will address those laboratory experiments in which the vertical excursions were the principal area of interest.

IV-A. NOAA OPS

The NOAA OPS program was initiated and sponsored by the National Oceanic and Atmospheric Administration (NOAA) and carried out by the Union Carbide Corporation in response to a need to extend scientific diving in the ocean. The biomedical research program was planned and executed by personnel of the US Naval Submarine Medical Research Laboratory (NSMRL), New London, Connecticut.

Purpose:

The purpose of the program was to develop and test decompression procedures and vertical excursion profiles, to study adaptation to nitrogen narcosis, and to assess further the stresses of two weeks of nitrogen saturation (Hamilton, Kenyon, Frietag and Schreiner 1973). Tables were needed which would serve the entire depth range in which a nitrogen-based habitat might be located.

Location:	Union Carbide Corporation, Environmental Physiology Laboratory, Tarrytown, New York
Dates:	October 17 1972 to January 25, 1973
Duration:	NOAA OPS I -- 18 days NOAA OPS II - 16 days
Saturation Depth:	NOAA OPS I -- 30, 90 feet NOAA OPS II - 60, 120 feet
Breathing Gas:	Storage gas -- Normoxic Oxygen--4.2 to 10.5% Excursion gas- Air
Subjects:	NOAA OPS I and II -- 3
Facility:	The experiments were performed in the Experimental Diving Facility operated by the Environmental Physiology Laboratory of the Union Carbide Research Institute.*

* This facility was dismantled in 1975 and relocated to Tarrytown Labs, Tarrytown, New York.

Facility Description:

The facility is shown schematically in Fig. 3. Four chambers comprise the complex, each largely independent of the others in operation and intended function. The main lock of the White Whale is a 5.5 x 7.5 foot cylinder with a volume of 138 cubic feet. The entry lock, 41 inches in diameter, adds another 37 cubic feet of volume to the system when it is open to the inside.

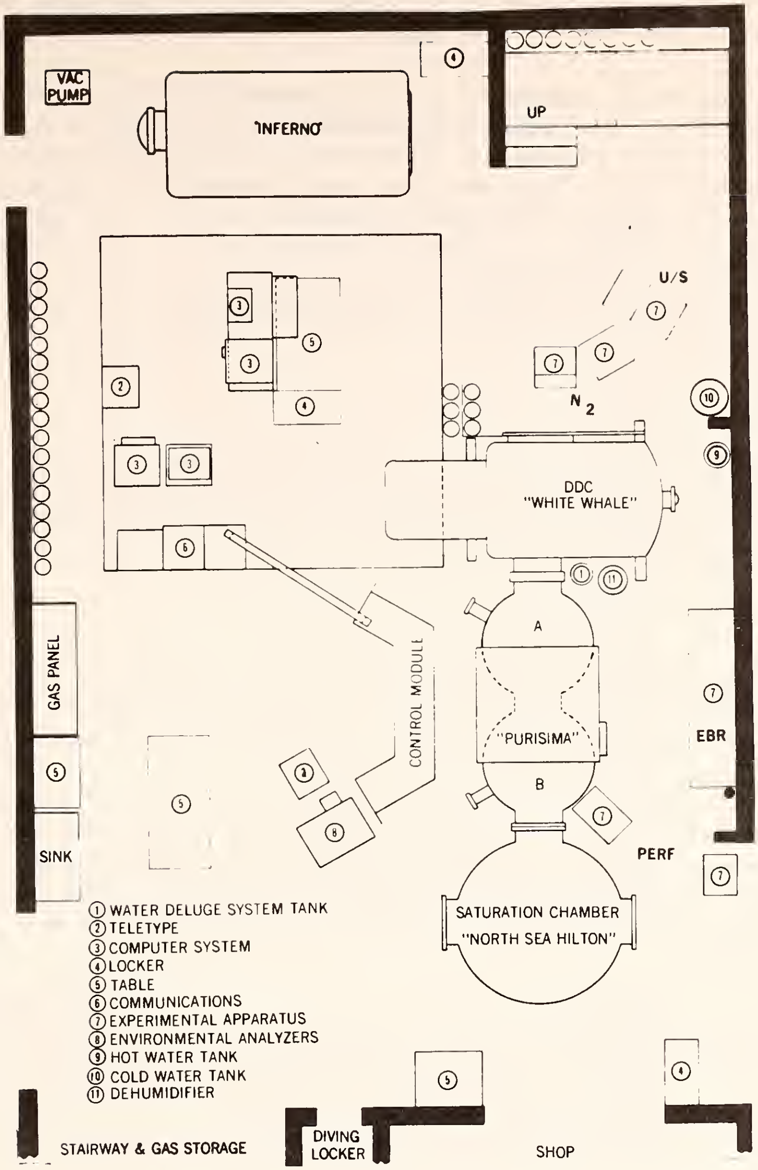

Fig. 3. Experimental diving facility used for NOAA-OPS.

The Purisima chamber consists of two interconnected spheres each five feet in diameter. The two chambers are designated A and B, with A connecting to the main lock of the White Whale. Two hatches between A and B permit them to be pressurized independently.

The primary function of the 7.5-foot North Sea Hilton is to provide a living area in which divers wash, eat and stretch out or stand up during long saturations.

The White Whale DDC is rated to 675 fsw, Purisima to 1,000 fsw and the North Sea Hilton to 600 fsw by the ASME code for unfired pressure vessels.

Most operations were conducted from the control module including pressurization, mask breathing, gas selection and pressure, supply and chamber pressure, timing, electrical system and fire extinguishing controls. Appropriate instruments were available for measuring gas composition, temperature, timing experiments, communicating, recording and video taping. An IBM 370 computer was used for developing the diving and excursion matrix and for the analysis of biochemical data. A 316 Minicomputer was used for maintaining a time base for experiments on subjects and for recording environmental data such as temperature and pressure.

Divers:

Six, male subjects were used during NOAA OPS ranging in age from 19 to 39. Five of the six divers had previous diving experience in the Union Carbide Laboratory. All were qualified scuba divers, in excellent health, and eager for the experience.

Procedure: (Calculation of the excursion matrix)

The overall experimental plan for the project called for the use of a data base from which new excursion tables could be developed. The best data available were used to serve as a base for formulation of the new matrix.

The data had to have certain characteristics. To be of maximum utility, they had to come from well-documented exposures of a suitable population in which decompression sickness had been encountered occasionally. Dives in which the mission or emotional involvement of the participants prevented accurate documentation of either the profile or decompression results would be of limited value.

Another special requirement was to have a broad range of exposures, as the nature of excursion diving from saturation dictates the need for variable matrix elements throughout a wide range of both times and depths. Because the NOAA OPS program involved saturation as well as no-decompression excursions during saturation, both slow and fast half-time tissue compartments were involved.

The data acquisition began with the nitrogen matrix developed by Workman (1965) which reflects the considerable experience of the US Navy in air diving. The search was expanded by direct inquiry to sources known to have well-documented data not considered in Workman's matrix. A listing of dives and their sources is given in Table 8. A total of 84 dives were processed which represented 189 man-exposures.

To use the gas loading matrix method of making the transition between past experience and future operations, a technique was developed permitting the weighting of each dive. Times, depths, and severity of each incident

TABLE 8

Data used in the development of the NOAA matrix 32/02

Origin of Data	Number of Dives	Number of Divers	Depth of Dives	Total bottom time of Dives (min)
Insitute for Aviation Medicine of the DFLVR, Germany	1	2	23m	6660
	2	6	23m	15000
	2	11	90m	5
	1	3	12m	480
	1	3	15m	450
	2	3	18m	450
	1	3	21m	360
	1	3	24m	360
	2	6	27m	240
	1	3	30m	240
	1	3	33m	180
	1	3	36m	180
	1	3	39m	180
	1	2	30m	3000
	1	2	40m	3000
	1	1	50m	3000
	1	1	60m	3000
	1	1	70m	2280
	1	1	70m	3000
	1	2	20m	8640
Naval Submarine Medical Center, New London, Conn.	1	1	55fsw	313
	1	1	55fsw	319
	1	1	55fsw	30
	1	1	58fsw	23
	1	2	45fsw	3600
	1	1	45fsw	1602
U.S. Navy Experimental Diving Unit, Washington, D.C.	2	4	33fsw	1440
	5	8	33fsw	2160
	3	4	99fsw	360
	3	4	99fsw	540
	1	4	99fsw	720
	3	6	140fsw	90
	3	6	140fsw	120
	6	12	140fsw	180
	8	16	140fsw	240
	3	6	140fsw	360

TABLE 8 (cont.)

Origin of Data	Number of Dives	Number of Divers	Depth of Dives	Total bottom time of Dives (min)
Ocean Systesm, Inc.,	1	2	200fsw	30
Tarrytown, N. Y.	1	2	400fsw	10
1970-1971	1	2	400fsw	30
	1	2	300fsw	35
J&J Marine,	2	2	33fsw	1440
Houston, Texas	1	2	30fsw	1440
	2	4	115fsw	360
	6	12	106fsw	360
	1	1	130fsw	720
	2	5	132fsw	720
	2	6	137fsw	720

of decompression sickness were considered, as well as the gas loading history of each compartment. Equivalent procedures also were followed for profiles which did not result in decompression sickness. Quantitative probabilities were assigned to each element in the matrix.

Subjective judgement was used instead of comprehensive statistical analyses. This proved to be efficient and effective for the data used. The matrix which resulted from this analysis is shown in Table 9. Note that M-values decrease with increasing half-times, and, that they increase by about 10 or 12 feet with each additional 10-foot depth increment.

Although this matrix allows the computation of successful tables, it has defects which might be remedied by additional data. For example, following the increase with depth beginning with the sixth compartment, a discontinuity is seen between 80 and 90 fsw. There is every reason to believe that these functions should be represented by smooth curves. More data however are needed in order to properly smooth them.

After completing a workable matrix, the no-decompression excursion bottom times were computed. The criterion for a no-decompression dive was simply that no compartment π value should violate the appropriate M-value. That is, the M-value is applicable to the point 10 fsw deeper than the storage depth. The compartment which allows the least amount of time at the bottom is the controlling tissue and that time is the no-decompression time for that depth. The NOAA OPS descending excursion profiles were calculated accordingly.

With saturation diving, not only is there the water and sea floor below, but also there exists an environment above the storage depth, which generally

TABLE 9

NOAA OPS constraint matrix 32/02

	M-values for each compartment with halftime values in min														
Depth	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
fsw	5	10	20	40	80	120	160	200	240	320	480	640	720	1000	1280
250	380	360	335	333	330	330	327	315	314	313	311	308	307	302	297
240	370	350	325	323	320	320	315	304	303	302	300	297	296	291	286
230	360	340	315	313	310	310	304	293	292	291	289	286	285	280	275
220	350	330	305	303	300	299	292	282	281	280	278	275	274	269	264
210	340	320	295	293	290	288	281	271	270	269	267	264	263	258	253
200	330	310	285	283	280	277	269	260	259	258	256	253	252	247	242
190	320	300	275	273	270	266	258	249	248	247	245	242	241	236	231
180	310	290	265	263	260	255	246	238	237	236	234	231	230	255	220
170	300	280	255	253	250	244	235	227	226	225	223	220	219	214	209
160	290	270	245	243	240	232	224	216	215	214	212	209	208	203	193
150	280	260	235	233	230	220	212	205	204	203	201	198	197	192	187
140	270	250	225	223	219	208	201	194	193	192	190	187	186	181	176
130	260	240	215	213	208	196	189	183	182	181	179	176	175	170	165
120	250	230	205	198	193	183	178	172	171	170	168	165	164	159	154
110	240	220	195	183	180	170	166	161	160	159	157	154	153	148	143
100	230	210	175	170	167	158	155	150	149	148	146	143	142	137	132
90	220	200	160	158	156	142	141	139	138	137	135	132	131	126	121
80	210	190	150	148	145	119	118	118	118	118	118	118	118	115	110
70	200	180	142	138	132	114	113	113	113	113	113	110	109	104	99
60	190	168	134	128	120	108	107	106	105	104	102	99	98	93	88
50	172	152	128	113	106	98	97	95	94	93	91	88	87	82	77
40	154	136	117	98	93	88	86	84	83	82	80	77	76	71	67
30	136	120	102	84	80	76	75	73	72	71	69	66	65	60	57
20	118	104	87	70	67	64	63	62	61	60	58	55	54	50	47
10	100	88	72	56	54	52	51	51	50	49	47	44	43	40	37

has not been accessible. To ascend shallower than the storage depth is in effect to begin decompression. According to the M-value concept, if the π values are below the M-values, then it is safe - with some degree of confidence - to ascend another 10 fsw. This process continues until a diver surfaces or is as shallow as he wishes to be. The M-values, however, imply that the diver is going to spend an indefinite amount of time at this shallower depth and does not consider the probability of bends for a brief period of violation. In fact, a diver can exist in a state of supersaturation which violates the M-value for a brief period of time, with an acceptable probability of bends, as long as he returns within a time limit which is consistent with that probability. Using this concept, ascending excursion times were computed.

In order to safely and effectively carry out the program, a total dive profile was devised for both phases. Gas loadings were accumulated continuously in the 11 compartments (up to 480 minutes) for each two-week exposure. The first excursion was begun with the gas loadings that prevailed at the end of 41 hours of equilibration at 30 fsw. After this excursion, re-equilibration to 30 fsw was allowed prior to the second excursion and so on. This resulted in one continuous gas loading record for the entire period. The excursions computed and tested for NOAA OPS I and II are given in Tables 10 and 11.

TABLE 10

Excursions computed and tested
(NOAA OPS I)

Day	Time	Depth fsw	Dive time (min)	Remarks
1	1700	30		Go to 30 fsw
2		30		
3	1000	120	62	
3	1400	120	60	
4	1000	85	316	
5	1000	200	10	
5	1400	200	10	
6	1000	100	104	
6	1400	100	100	
7	1000	150	30	
7	1400		30	
7	2000	90		Go to 90 fsw
8				
9	1000	175	300	
10	1000	60	35	Ascending excursion
10	1400	40	20	" " "
11	1000	200	51	
11	1400	200	50	
12	1000	40	10	Ascending excursion
12	1400	60	35	" " "
13	1000	250	22	
13	1400	250	22	
13	1730	90		Begin decompression
14	1500			Decompression complete

Computations for OPS I excursions were "square wave", in that a 10-minute dive implies departure from habitat and arrival at excursion depth at the same instant, and the reverse at the end of the excursion. In practice, the corners were cut so as to approximate the same gas-pressure exposure in tests as was calculated.

TABLE 11

Excursions computed and tested
(NOAA OPS II)

Day	Time	Depth fsw	Dive time (min)	Remarks
1	1900	0		Go to 120 fsw
2		120		
3	1000	250	53	
3	1400	250	53	
4	1000	75	37	Ascending excursion
4	1400	55	9	" " "
5	1000	55	8	" " "
5	1400	75	39	" " "
6	1000	200	360	
7	1000	300	18	
7	1400	300	18	
7	1800	120		Begin decompression
8	0848	60		Arrive at 60 fsw
9	1000	150	72	
9	1400	150	72	
10	1000	115	347	
11	1000	5	13	
11	1400	5	16	
12	1000	200	22	
12	1400	200	22	
12	1800	60		
13	1121	0		Begin decompression Surface

In OPS II the computations were improved so as to account for compressions and decompressions. These were not included in bottom times. The tests followed the calculated profile quite closely.

Because of the lack of any significant signs or symptoms of decompression sickness, the computed allowable time for OPS II was extended by 25% for the ascending excursions. These tests resulted in mild bends pain in one subject, suggesting that the original computations approached the safe limits.

The excursion depths were chosen to provide a good range of testing, and to provide suitable exposures for performance monitoring. For example, 200 fsw and 250 fsw were repeated as often as possible to permit replication of tests during excursions. The environmental parameters existing during the program are shown in Table 12.

TABLE 12

NOAA OPS environmental parameters

Parameter	Saturation depth (fsw)	Typical range	High	Low
Oxygen (per cent atm)				
OPS I	30	10.5 - 11.0	12.8	9.3
		0.20 - 0.21	0.24	0.18
	90	5.2 - 5.6	7.0	4.6
		0.19 - 0.21	0.26	0.17
OPS II	120	3.9 - 4.6	5.6	3.5
		0.18 - 0.21	0.26	0.16
	60	7.2 - 7.8	8.5	6.6
		0.20 - 0.22	0.24	0.19
Carbon Dioxide (mm Hg)				
OPS I	30	6.5 - 8.5	13.8	4.2
	90	6.0 - 8.0	12.8	2.0
OPS II	120	4.0 - 6.5	12.3	2.0
	60	7.5 - 9.5	17.5	4.2
Temperature (°C)				
OPS I	30	22.7 ± 1°C		
	40	22.7 ± 1°C		
	120	23.0 ± 1°C	25.8	17.0
	60	25.0 ± 1°C	29.9	23.1
Relative Humidity (per cent)				
OPS II	120	65 - 75	96	39
	60	50 - 60	66	35

Experiments:

An extensive series of physiological and medical experiments were carried out during the program. These experiments are listed in Table 13. Descriptions of each of these studies can also be found elsewhere (Schaefer and Dougherty 1976; Langley 1973, Kinney, Luria, Strauss, McKay and Paulsen 1974; Kinney, Luria and Strauss 1974; Moeller 1974; Schmidt, Moeller, Hamilton and Chattin 1974; Langley and Hamilton 1975).

General Procedures:

The program was divided into two 2-week saturation exposures. The saturation depths were 30 and 90 fsw, and 60-and 120 fsw in NOAA OPS I and II respectively.

TABLE 13

NOAA OPS biomedical experiments

Assessment of Decompression
1. Nitrogen washout
2. Doppler Ultrasonic bubble detection
3. Throughpass ultrasound
4. Bone density

Nitrogen Narcosis
1. Psychomotor and cognitive performance
2. Somatic evoked brain responses
3. Visual evoked brain responses

Tolerance of Exposure
1. Biochemistry
2. Dental-Oral tissue response
3. Aerobiology
4. Salivary microbiology
5. Immunology and ecology
6. Psychology

Longitudinal Health Study

The order of excursions was varied because of the interaction of adjacent profiles and to avoid any consistent patterns. It was considered important to test ascending excursions the day after a long descending excursion. The order of presentation of the excursions is shown also in Tables 10 and 11. Two excursions were conducted each day. One at 1000 and one at 1400 hours.

Pre- and post-saturation bounce dives were conducted to observe the effect on narcosis of direct descent to the same depth from saturation. When possible, the same depths were used for excursions from various storage

depths. These bounce dives also provided a baseline for use of the bubble detecting apparatus. Three were scheduled before and after each saturation (although not all were accomplished). Work routines of under 10 minutes were used. A particular excursion may have had one, two, or three such cycles. Each of the three chambers was arranged for certain activities and the divers moved about according to a rotation schedule.

For descending excursions, performance tests and measurements of evoked brain response were administered upon arrival at the excursion depth. Near the end of an excursion, attention was focused on decompression studies including the nitrogen washout, ultrasonic and Doppler experiments. During ascending excursions, the decompression studies began at the beginning of the excursion and continued until after recompression to saturation depth.

During the first week of NOAA OPS II, one subject was stricken with influenza and was decompressed from 120 fsw to the surface without incident.

Medical coverage in NOAA OPS consisted of pre- and post-dive examination of the divers and medical surveillance during the dive. The examinations were given as part of the Longitudinal Health Study, an ongoing program at New London. This is a thorough medical and dental examination, and by a diver's entry into the program he will be given periodic examinations, including long bone x-rays as long as the program continues.

Decompression Procedures:

The saturation decompressions carried out are shown in Table 14. Three divers were decompressed from 90 fsw, one diver from 120 fsw and two divers from 60 fsw. In addition, two divers were decompressed from 120 feet to 60 fsw. Decompression was conducted in a continuous mode for both NOAA OPS I and II. A continuous decompression means that at no time does the rate of decompression exceed a maximum level, based on a given criteria. It also means there are no decompression stops, although a stop can always be interposed if needed.

In NOAA OPS I decompression from 90 fsw began three hours and eight minutes following a 22 minute descending excursion to 250 fsw. It was completed 21 1/2 hours later with no signs of decompression sickness being observed. The criteria used were modified Ocean Systems Inc. and US Navy helium saturation procedures.

Decompression for NOAA OPS II began three hours and 38 minutes after a 22 minute, 200 fsw excursion. Continuous decompression procedures were employed using 1/4 fsw intervals for the greatest possible gas elimination. The total decompression time from 60 fsw was 17 hours and 11 minutes. The final rate of ascent was 34 min/ft which was necessary only for the last two fsw. Oxygen breathing was not employed for decompression purposes, however, it was used for nitrogen washout studies performed by NSMRL for short periods of time. The oxygen was increased to 20.8 ± 0.2% before the start of decompression. No symptoms of decompression sickness were reported.

TABLE 14

Summary of decompressions from NOAA OPS saturation

NOAA OPS I

Criteria: Modified Ocean Systems Inc. and U.S. Navy helium saturation procedures.

90 fsw to sea level (Time: 1380 min)

- 6 min/ft to 60 fsw	Oxygen 8 → 11%
-15 min/ft to 40 fsw	Oxygen 17 → 21%
-15 min/ft to 30 fsw	Oxygen 21%
-20 min/ft to 20 fsw	Oxygen 21%
-25 min/ft to 10 fsw	Oxygen 21%
-30 min/ft to sea level	Oxygen 21%

NOAA OPS II

Criteria: 480 min compartment; Matrix 32/02; continuous; 1/4 fsw intervals.

120 fsw to surface (for sick subject) (Time: 1842 min)

- 6 min/ft to 90 fsw	Oxygen 16.4%
- 6 min/ft to 70 fsw	Oxygen 21%
-15 min/ft to 47 fsw	Oxygen 21%
-20 min/ft to 18 fsw	Oxygen 21%
-25 min/ft to sea level	Oxygen 21%

120 fsw to 60 fsw (Time: 888 min)

- 6 min/ft to 92 fsw	Oxygen 7.5%
-20 min/ft to 80 fsw	Oxygen 7.5%
-24 min/ft to 60 fsw	Oxygen 7.5%

60 fsw to surface (Time: 1032 min)

- 6 min/ft to 30 fsw	Oxygen 21%
-22 to -27 min/ft to 20 fsw	Oxygen 21%
-27 to -30 min/ft to 10 fsw	Oxygen 21%
-30 to -34 min/ft to sea level	Oxygen 21%

NOAA OPS decompression times were much shorter than those used for Tektite and FLARE. Because the small number of subjects involved in NOAA OPS provided little statistical confidence in the results, they must be viewed with caution. It should be pointed out that although the decompression profiles in saturation diving are dependent on a single limiting compartment (the slowest), the rates can change as the matrix changes with depth. A significant relevant factor is the rate of pressure reduction. Early saturation decompression (Hamilton, MacInnis, Noble and Schreiner 1966) began with a large initial first stop of perhaps 25 fsw to set up a gradient, which may, in fact, produce bubbles. The fastest travel used in NOAA OPS was a six minute-per-foot ascent. As an additional precaution, the divers were required to ingest more fluids than usual and encouraged to move around frequently, although they were allowed to sleep during decompression.

One reason for a greater rate of ascent than used by others, even though the half-times of the limiting compartments are similar, is the fact that a variable matrix was used which permits a faster rate of ascent for a given compartment at greater depths. Another factor to consider is that no oxygen breathing was used during any decompressions. There is no doubt that oxygen helps in decompression and is indispensible in treatment, but its benefits in clearing the slowest compartment may be limited. More studies are needed in order to resolve this issue.

Results:

Two 14-day, dry chamber saturation experiments were completed. Three subjects took part in each experiment which involved saturation at depths of 30, 60, 90 and 120 fsw. A total of 18 ascending and 15 descending excursions were successfully completed constituting over 75 man-excursions.

A technique was developed and utilized for extracting data from previous dives, using a combination of computer and manual methods. Tables were computed using the new matrix and a decompression model involving 11 gas loading compartments was constructed in which the longest limiting half-time used was 480 minutes. This method produced successful tables on the first approach.

Descending excursions included depths ranging from 85 to 300 fsw while ascents ranged from 30 to 65 fsw above the saturation depth. Excursion times ranged from eight minutes to six hours. The excursion profiles derived from the matrix are shown in Tables 15 and 16. The permissable excursion times shown in these tables are not exactly the same as those shown earlier on Tables 10 and 11 due to a general effort to be conservative in the publication of recommended excursion profiles.

The criteria and instructions for use of these tables are summarized below. More detailed information including examples of excursion dives may be found in the NOAA Diving Manual (1975).

TABLE 15

No-decompression ascending excursion times (min)

Habitat Depth fsw	Excursion Depth (fsw) 0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90
30		48	60	*	*	*	*												
35		37	48	60	*	*	*	*											
40		31	40	52	60	*	*	*	*										
45		24	31	40	52	60	*	*	*	*									
50		18	25	32	42	60	*	*	*	*	*								
55		13	18	25	32	42	60	*	*	*	*	*							
60		7	13	18	25	32	42	60	*	*	*	*	*						
65		-	8	14	20	27	34	44	60	*	*	*	*	*					
70		-	-	8	14	20	27	34	44	60	*	*	*	*	*				
75		-	-	-	9	15	21	28	36	47	60	*	*	*	*	*			
80	-	-	-	-	-	9	15	21	28	36	47	60	*	*	*	*	*		
85	-	-	-	-	-	5	10	16	23	30	37	48	60	*	*	*	*	*	
90	-	-	-	-	-	-	5	10	16	23	30	37	48	60	*	*	*	*	*
95	-	-	-	-	-	-	-	6	12	18	24	31	40	52	60	*	*	*	*
100	-	-	-	-	-	-	-	-	6	12	18	24	31	40	52	60	*	*	*
105	-	-	-	-	-	-	-	-	-	7	13	18	25	32	42	60	*	*	*
110	-	-	-	-	-	-	-	-	-	-	7	13	18	25	32	42	60	*	*
115	-	-	-	-	-	-	-	-	-	-	-	7	13	18	25	32	42	60	*
120	-	-	-	-	-	-	-	-	-	-	-	-	7	13	18	25	32	42	60

* No time limit

TABLE 16

No-decompression descending excursion times (min)

Habitat Depth fsw	Excursion Depth (fsw) 80	85	90	95	100	105	110	115	120	125	130	135	140	145	150	155	160
30	350	267	156	113	91	78	68	60	55	50	45	40	36	32	28	24	22
35	*	*	283	229	143	108	89	77	68	61	54	46	41	37	34	31	28
40	*	*	*	301	240	202	147	112	92	80	70	59	50	44	39	35	32
45	*	*	*	*	323	253	210	181	137	108	91	69	56	48	42	38	34
50	*	*	*	*	*	350	267	219	187	164	140	86	64	53	45	40	36
55	*	*	*	*	*	*	314	245	203	174	153	137	86	63	52	45	40
60	*	*	*	*	*	*	*	284	224	187	161	142	127	85	63	52	45
65	*	*	*	*	*	*	*	315	236	191	162	145	128	111	85	63	51
70	*	*	*	*	*	*	*	*	279	213	174	148	129	114	103	84	62
75	*	*	*	*	*	*	*	*	*	*	*	288	228	191	165	145	95
80		*	*	*	*	*	*	*	*	*	*	*	*	*	317	225	215
85			*	*	*	*	*	*	*	*	*	*	*	*	*	*	328
90				*	*	*	*	*	*	*	*	*	*	*	*	*	*
95					*	*	*	*	*	*	*	*	*	*	*	*	*
100						*	*	*	*	*	*	*	*	*	*	*	*
105							*	*	*	*	*	*	*	*	*	*	*
110								*	*	*	*	*	*	*	*	*	*
115									*	*	*	*	*	*	*	*	*
120										*	*	*	*	*	*	*	*

Habitat Depth fsw	165	170	175	180	185	190	195	200	205	210	215	220	225	230	235	240	245	250
30	18	15	13	12	11	10	9	8	8	7	7	6	6	5	5	5	5	-
35	25	22	20	16	14	13	11	10	9	9	8	7	7	6	6	6	5	5
40	30	28	25	23	21	17	15	13	12	11	10	9	8	8	7	7	6	6
45	31	29	27	25	23	22	21	18	16	14	12	11	10	9	9	8	8	7
50	33	30	28	26	24	22	21	20	19	18	16	14	13	12	11	10	9	8
55	36	32	30	27	25	24	22	21	20	19	18	17	15	13	12	11	10	9
60	39	35	32	29	27	25	23	22	21	19	18	17	17	15	13	12	11	10
65	44	39	35	32	29	27	25	23	22	20	19	18	17	16	16	14	12	11
70	51	44	39	35	31	29	26	25	23	21	20	19	18	17	16	15	14	13
75	66	53	45	40	35	32	29	27	25	23	22	20	19	18	17	16	16	15
80	122	70	55	47	41	36	32	29	27	25	23	22	20	19	18	17	16	15
85	265	225	95	66	54	46	40	36	32	29	27	25	23	22	22	19	18	17
90	*	339	275	168	97	68	55	47	41	37	33	30	28	26	24	23	21	20
95	*	*	*	306	227	143	113	80	62	52	46	40	37	33	31	28	26	25
100	*	*	*	*	341	281	193	135	109	93	72	59	50	44	40	36	33	31
105	*	*	*	*	*	354	308	262	174	129	107	77	62	53	46	41	38	35
110	*	*	*	*	*	*	*	334	294	257	176	132	83	65	55	48	43	39
115	*	*	*	*	*	*	*	*	347	303	270	243	163	91	68	57	49	44
120	*	*	*	*	*	*	*	*	*	*	329	291	261	237	101	72	59	51

* No time limit

Criteria for Computation

15 compartment decompression model, only 11 in use
Half-times 5-480 min.
Matrix 32/02.
Inert gas: nitrogen only.
Habitat gas composition: PO_2 = 0.2 atm, balance N_2.
Excursion gas: Air
Excursion times rounded down to next minute.

Validation

Tested at Habitat depths 30, 60, 90, 120 fsw.
Descending excursions tested: 85-300 fsw.
Ascending excursions tested: 5-85 fsw.
J-factors: Ascending: Some tests done with times increased by 25%: Times calculated for depth 5 fsw shallower than presented here.
Descending: Times calculated for 5 fsw deeper; descent time was not included in bottom time for test dives (OPS II).

General Criteria

A dive which loads slow tissue (half-time) compartments prejudices subsequent dives which are limited by these compartments. No-stop dives, however, which are short, do not appreciably affect subsequent dives after a suitable time interval. A most important factor is the degree to which a given dive approaches the time limit for that depth; one which runs to the maximum allowable time will likely have more effect than one which does not. A four-hour period at storage depth should precede any repetitive dive.

Descending Excursion

A short descending excursion from saturation has little effect on subsequent descending dives, short or long (following the four-hour interval at storage depth) although it may have an effect on subsequent ascents. An 18-hour interval should be observed if limits were approached.

Following a six-hour excursion 30 fsw below storage depth, a subsequent ascending excursion, if it approaches limits, should not take place sooner than 36-hours. Following a long excursion only a few feet below storage depth, subsequent ascents should be safe if computed from the depth of the first excursion, rather than from storage depth.

Begin timing excursions on departure from the habitat depth (bottom time includes descent time). Descend at a moderate rate keeping in mind that a slow descent is preferred, but reduce bottom time. Return to storage depth at any desired rate up to 30 fpm.

Ascending Excursions

Ascending excursions do not prejudice subsequent ascents or descents, but a four-hour interval is recommended. Begin timing ascents on arrival at excursion depth (bottom time does not include transit times). Ascend at 10 to 20 fpm. Descend at 60 fpm or faster if desired. If bend symptoms are noted, return immediately to the storage depth. If return to storage depth is delayed by ear problems, it is preferable to discontinue descent (or even momentarily ascend a bit) and clear the ear, rather than incur ear damage in order to adhere strictly to the table.

Repetitive Dives

Excursion diving from saturation may be sensitive to recent diving history. General rules cannot easily be given. Procedures conservative enough for all eventualities will make the practice inefficient in normal usage. For this reason, good judgement must be the controlling factor. The guidelines given here are intended to provide the background necessary to enable good judgement to be used. Many factors change the conditions, such as cold, workloads, equipment used, experience, etc. All such factors must be considered in any situation. The suggestions given here are based on computed gas loadings and have been given only limited testing. They may need to be modified in the light of relevant experience and are not intended to be precise.

Biomedical Experiments

The biomedical studies carried out were listed on Table 13. Generally speaking, no serious problems were encountered. The results of these experiments may be summarized as follows.

1. Nitrogen Washout

OPS I - in saturated excursion dives three subjects were exposed to air pressure equivalent to 30 fsw for one week and performed subsequently two excursion dives to 150 fsw. Following decompression back to 30 fsw, the subjects breathed oxygen. Expired air was monitored in the three subjects in intervals with a mass spectrometer. In one subject who experienced mild knee pain, nitrogen bursts were found repeatedly in the expired air during decompression while breathing oxygen. The occasional nitrogen bursts were associated with sounds which might have been due to bubbles as detected with the Doppler ultrasound bubble detector.

OPS II - Nitrogen bursts were detected on four occasions: Following decompression to 5 fsw from 60 fsw, two subjects had bends symptoms (itching, tingling) at the same time. One subject had symptoms following a decompression from 120 fsw to 75 fsw. Another subject had the same symptoms following ascent from 120 fsw to 55 fsw. Both of these subjects also had bends symptoms such as itching during the time the nitrogen bursts occurred.

The finding of nitrogen bursts following a complete initial washout during oxygen breathing has been interpreted as nitrogen elimination from "silent" nitrogen bubbles, due to a nitrogen gradient set up by oxygen breathing. Lung function tests carried out on some of these subjects at normal atmospheric pressure did not reveal signs of any abnormalities, e.g., air trapping.

2. Doppler Ultrasonic Bubble Detection

No unequivocal bubble sounds were heard during NOAA OPS I and II. Interpretation is continuing to determine the nature of certain unidentified sounds. Spectral analysis of sounds is in progress.

3. Throughpass Ultrasound

No attentuation was noted, although this technique has been successful in detecting bubble formation in animal decompression. That no bubbles were detected is not conclusive proof that none were there, however, other testing seems to corroborate the conclusion that few or no bubbles were present during decompression.

4. Bone Density

In NOAA OPS I, one subject showed a clear reduction in bone density. A second subject showed a net decrease in density, but results were less definitive. The third subject showed no change in density.

5. Nitrogen Narcosis

This study was intended to discover if there were deleterious neurobehavioral effects of prolonged exposure to normoxic hyperbaric nitrogen and, if so, would such exposures provide resistance to narcosis during excursions to greater depths.

At the beginning of saturation, performance equalled or exceeded that obtained in pre-saturation control tests, and it continued to improve slightly, but regularly, at saturation depths throughout the exposures. Evidently, the cognitive and perceptual-motor functions tested were not impaired by residence in the normoxic equivalents of 120 fsw, or less. Performance decrement during downward excursions varied directly with depth and inversely with duration of saturation exposure.

On excursions, the divers generally described the narcosis as being about equivalent to an air dive to a depth equal to the excursion depth minus the saturation depth. A certain amount of this subjective judgement is undoubtedly related to the feeling of both divers and investigators that this is what should be expected. This concept apparently does not hold true at all depths, since divers making excursions to 300 fsw from 120 fsw saturation were definitely and seriously affected. There was some adaptation but it was not sufficient to make 300-foot diving with air safe, even from a 120 fsw satura-

tion depth. On the other hand, at 250 fsw, divers were able to feel narcosis but felt safe. Even from 60 fsw, divers at 200 fsw felt narcosis but did not elicit symptoms as marked as they would have if making the same excursion from the surface.

6. Psychomotor and Cognitive Performance

Performance on all tests continued to approach a final level asymptotically during exposure to habitat nitrogen partial pressure levels. Exposures to increased PN_2 during excursions caused substantial depth-dependent results in most performance scores. Despite the restrictions on sample size imposed by the nature of the study, subject illnesses unrelated to exposure parameters, and tracking test equipment malfunctions, the evidence for the trends just described is clear.

Absence of performance impairment during residence at 120 fsw or less was most likely due to the narcotic potency at these depths being below the threshold of detection with the tests used. The progressive amelioration of narcotic effects during excursions with time under saturation was probably a result of a combination of factors, and not necessarily only adaptation.

From a practical point of view it seems certain that duration of saturation exposure and frequency of excursion to a particular depth would invariably covary. Under those circumstances diving operations should be planned to capitalize on the dramatic decrease in performance impairment with successive excursions. A detailed description of the psychomotor program may be found in Schmidt, Moeller, Hamilton and Chattin (1974).

7. Somatic Evoked Brain Responses (EBR)

Somatic EBR showed occasional but not completely consistent pressure-dependent decrements on exposure of subjects to increased PN_2. In most cases this decrement was reduced if the subject was adapted to nitrogen. A definite reduction in control (e.g., not on excursions) EBR was seen in one subject during adaptation at 90 fsw, as compared to pre- and post-dive values. EBR data agreed in general with observations on performance but is not consistent among all subjects. Moderate neurologic adaptation was indicated. Reliability of somatic EBR for assessing diver response to narcosis was inconclusive.

8. Visual Evoked Brain Response (VER)

Some measures of the VER showed decrements commonly seen in narcosis, and some did not. Those that did show decrements also showed evidence of adaptation. The adaptation was not complete however since the data at the end of the saturation period did not show a complete return to the levels measured at the surface. Analysis of the EEG's of the diver-subjects during the course of the two-week saturation period at depth revealed two changes. First, the frequency and the amplitude of alpha activity was reduced when compared to surface measures made prior to and following the saturation period.

Second, the amplitude of theta activity rose considerably for two of the men; there was no change in theta for the other three during the same time period.

There is some preliminary evidence here for adaptation. The lack of decrement and hence adaptation in some subjects may be a reflection of their high level of experience in the diving environment.

9. Tolerance of Exposure

No objective data yet available indicate in any way that the subjects had difficulty living in the hyperbaric nitrogen environment. However, all three subjects exposed to 120 fsw were feeling ill during the course of that week. As mentioned earlier, one subject was so sick with influenza, he had to be removed from the experiment. The other two subjects were not feeling well, either.

With three subjects known to be sick, it could not be determined how much effect the hyperbaric nitrogen had on their well-being. This experiment was deeper by 20 percent than the Tektite II test which disclosed essentially no difficulty (Lambertsen and Wright 1973). The question remains as to whether some of the illness seen at 120 fsw in OPS II was due to the nitrogen. Observations by both subjects and experimenters concluded that it was not, and that even deeper saturation could be safely carried out with nitrogen.

10. Biochemistry

Hematology - Plasma fibrinogen fluctuated during individual dives--apparently responding to pressure changes--and was notably elevated during the 120 fsw saturation. Platelets decreased at 90 fsw and increased at 120 fsw, i.e., they were lower during the second week of each experimental series after being slightly elevated during the first week. Decompression from saturation seemed to have produced increased platelet levels. A marked lengthening in whole blood clotting time (measured only in OPS II) occurred during the 120 fsw saturation run and after final deocmpression. A possible rise in total RBC's or a change in normal hemoglobin-hematocrit relationship seemed to occur after final decompression in each series. White blood cell counts showed considerable fluctuation.

Serum chemistry - Sporadic increases were seen in activity of lactic dehydrogenase, creatine phosphokinase, glutamic-oxalacetic transaminase and alkaline phosphatase which frequently could be related to major changes in environmental pressure.

Urine - Total urine protein output showed marked fluctuations, the peaks of which also appeared to follow major changes in pressure. Peaks of excretion of calcium, phosphate, osmolarity, urea nitrogen, steroid hormones, and to a somewhat lesser extent, creatinine, coincide with the 60', 90', and 120' series of pressure exposures. Hydroxy-proline excretion (an index of bone metabolism) appeared to increase in the higher pressure exposures.

11. Dental-Oral Tissue Response

During OPS I, small erythematous areas were noted on the palate of two divers after decompression. During OPS II, the same type of response was observed after decompression from bounce dives to 200 and 250 fsw. Some evidence of oral hygiene deterioration was manifested in "canker sore" formulation.

Visual observation and symptomatic suggestion of palatal response to decompression suggests an additional source for monitoring tissue reflections of gaseous saturation. The methodology for quantitating such phenomena currently is being refined.

12. Aerobiology

Since the total viable particle counts were essentially unchanged during OPS I, the sampling time was extended, during OPS II, producing interesting profiles. The density of bacteria-laden particula seemed to parallel activity patterns relative to illness and foreign intrusion. Viable particula increased markedly on days immediately subsequent to viral illness of one subject and to entry of a new subject and to visitations by guests.

13. Salivary Microbiology

Logistic problems during OPS I made conclusions concerning assays of fresh specimens highly speculative. All samples from OPS II were quick-frozen on site and then transported for processing. The following results relate primarily to data obtained during OPS II.

While overall salivary bacterial counts remained essentially constant throughout baseline, experimental and post-dive periods, specific organismal groups showed considerable variation. One result of habitat living was manifested by increased growth on EMB media. Variations in salivary staphylococci, streptococci and lactobacilli seemed to parallel oro-pharyngeal involvement in illnesses observed in three subjects.

Bacterial counts subsequent to thawing of frozen specimens were generally lower than those of corresponding fresh specimens, however the degree of reduction was usually no more than one $\log_{10}$ per ml. The salivary microflora appeared to reflect environmental adaptation and oro-pharyngeal illness patterns.

14. Immunology and Ecology

Divers provided nasal washings daily, which were frozen and analyzed for immunoglobulins. Concomitant serum immunoglobulin analysis was performed. Analytical emphasis was placed on quantitation of the serum and secretory immunoglobulins, transfer proteins and protease inhibitor levels in pre-dive, dive, and post-dive periods. Instrumentation difficulties have prevented completion of these analyses.

15. Psychology

(NOAA OPS I only.) Some moderately intense signs of anxiety and tension were observed in one subject. Information was obtained pertaining to the correlation between pain tolerance and other subjective symptoms as a function of pressure variation, particularly during excursions. There was no substantive evidence that emotional stresses were cumulative under these environmental conditions. The changes in subjective indices of stress were small in OPS I and did not appear to covary with pressure fluctuation. Therefore the program was not continued in OPS II.

16. Longitudinal Health Study

The NOAA OPS subjects participated in a longitudinal health study, a continuing medical survey of Navy officers and men, and a few civilians, engaged in diving and submarine activities. The intent is to learn about special medical factors affecting this group. Participants are given a thorough medical examination at the beginning and periodic examinations subsequently. No general medical findings were encountered in these examinations that could be related to the exposure to the nitrogen environment.

Conclusions:

In brief, the NOAA OPS program demonstrated the viability of living at depths up to 120 fsw in a normoxic atmosphere and the techniques of making vertical excursions on air to depths ranging from 5 to 300 fsw. The program paved the way for using air much more extensively than heretofore thought possible. In addition, it spawned several subsequent programs which were carried out both in the laboratory and in the open sea. Several of these programs are described in this report.

IV-B SHAD (Shallow Habitat Air Diving)

Introduction:

The SHAD program was initiated in January 1972 at the Naval Submarine Medical Research Laboratory (NSMRL) to further evaluate the biomedical feasibility of long-term residence in a compressed air environment. Vertical excursions were carried out to establish profiles that could be utilized by the air-saturated working diver and to obtain information relating to emergency conditions that might be encountered.

The fundamental difference between this program and NOAA OPS is that the SHAD divers breathed air both as a storage and excursion gas. Air saturation diving by its very nature embraces potential limitations related to oxygen toxicity, nitrogen narcosis, and gas density. As already described, previous studies have revealed the nature of some of these problems. Experiments at the storage depths planned for the SHAD program were conducted

first using a model animal system without evidence of adverse effects. As a result of these observations plus those obtained during a three-day manned air exposure at 50 fsw, the SHAD program was designed to place men in a compressed air environment at 50 and 60 fsw for a maximum of 30 days. A no-decompression excursion dive regimen permitting excursions between 5 and 250 fsw was constructed on a mathematical basis similar to that employed in the NOAA OPS I and II.

Purpose:

SHAD was designed principally as a biomedical feasibility program. As such, a multi-disciplinary scientific effort was undertaken to evaluate the divers both for obvious physiological limitations and such subtle physiological variances as could be anticipated. Emphasis was on pulmonary physiology, visual physiology, psychophysiology, hematology, and the chemistry and biochemistry of both urine and blood. Numerous additional biomedical studies also were completed.

Location:	Naval Submarine Medical Research Laboratory, (NSMRL), New London, Connecticut
Dates:	SHAD I - October 1973 SHAD II - May 1974 SHAD III - December 1974
Duration:	SHAD I - 29.5 days SHAD II - 28 days SHAD III - 9 days
Saturation Depth:	SHAD I - 50 feet SHAD II - 60 feet SHAD III - 50 feet
Breathing Gas:	Storage - Air Excursions - Air
Subjects:	SHAD I - 2 SHAD II - 2 SHAD III - 3

Facility:

The hyperbaric complex at NSMRL was utilized for the SHAD program. The same chamber complex was used in Project Genesis, the preliminary project that evolved into the US Navy's SEALAB program (Bond 1970) and in Tektite I, a long term man-in-the-sea project that employed a nitrogen/oxygen breathing mixture (Pauli and Cole 1970).

The principal hyperbaric chamber for SHAD was nine feet in diameter, with an inner lock 15 feet long and an outer lock nine feet long. Independent life support systems for controlling carbon dioxide, temperature and humidity were available in each lock. A small item transfer lock was available in the inner lock. Independent lighting, as well as visual and audio communication systems were present in each lock. Manual, chamber-mounted controls were used to maintain a constant storage depth (±0.5 fsw) and to add oxygen for maintenance of the required oxygen partial pressure. Depth, temperature, humidity, carbon dioxide, carbon monoxide, and oxygen levels were manually recorded from redundant monitoring systems, with trace gas impurities being monitored by gas chromatographic techniques. Sanitary facilities were available in the outer lock. Biomedical equipment was either retained inside the complex or transferred into the chamber when required. An immersion tank (wet pot) was not available. Mask-supplied contingency gases were available at all times.

A second, double-lock chamber was available for emergencies. The projected available surface interval for the saturated diver would have permitted safe transfer into this second chamber as well as to other chamber facilities accessable within the surface interval.

Divers:

All subjects taking part in SHAD had volunteered and were qualified US Navy divers under 30 years of age.

Procedure:

Four manned air saturation dives were carried out as part of the SHAD program. The general characteristics of these dives are shown in Table 17. Each of the nine saturated divers was given a complete physical examination and baseline biomedical tests prior to the dive. In addition, each diver was cross-trained in the data aquisition techniques used during the experiments.

The biomedical tests carried out during the SHAD series are shown in Table 18. With the exception of pulmonary function evaluations and human factors evaluations on excursion dive days, most data collection occurred on a one- or two-day cycle. Pulmonary function evaluations utilizing a wedge spirometer were made about four times each day during the initial days of each dive but on a decreasing frequency as the dive progressed. As time permitted, pulmonary function evaluations also were made during each descending excursion. Human factors evaluations were conducted prior to and during each excursion to 100 fsw or greater. A pre-cordial Doppler detector system was used during every ascent to determine the presence or absence of circulating gas bubbles. Consistent with the program goals, a medical officer entered the chamber each morning and examined the divers. The results of the biomedical monitoring and physical examinations were used to determine whether the dive would continue.

TABLE 17

General characteristics of SHAD dives*

Dive	Pre SHAD I	SHAD I	SHAD II	SHAD III
Date	Sept 1973	Oct 1973	Mar 1974	Dec 1974
Storage Depth (fsw)	50	50	60	50
No. of Divers	2	2	2	3
Duration, Total (days)	2.25	29.5	28	9
Mean Oxygen Level (AtA)[a]	0.51	0.51	0.57	0.61
Mean Carbon Dioxide Level[a,b]	0.111	0.092	0.099	0.172
Mean Temperature (°F)[a]	78.0	76.8	73.0	75.8
Mean Relative Humidity (%)[a]	76.0	62	52	74.7
No. Ascending Excursions	0	4	4	0
No. Descending Excursions	0	14	11	6
Decompression Time (min)	57.4	810	1680	2778[c]
Decompression Sickness[d]	yes (2)	No	No	yes (1)

* Compressed air with oxygen make-up was the only gas employed

a Storage depth values except for SHAD III, where a weighted mean reflective of the eight hours per excursion day spent at 100 fsw, was employed

b per cent, surface equivalent

c includes treatment regimen with 100% oxygen and recompression

d ( ) indicates number of divers affected

TABLE 18

Principal biomedical evaluations in the SHAD program*

Pulmonary

Pulmonary function (FVC, FEV, FEV_2, MEFR, MIFR, MVV)[a]
Gas exchange (BTPS, BPM, V_t, $Paco_2$, Vco_2, RQ) [I]
Inspired/expired gas analysis
Excercise tolerance
Carbon dioxide tolerance
Mixed venous blood gases

Vision

Visual evoked response
EEG
Fundus photography
Night vision sensitivity
Visual fields and acuity
Color vision [I]

Human Factors

Adaptive tracking
Mental arithmetic
Short term memory
Sentence comprehension
Pattern recognition

General Physical Parameters

General physical examination
Weight
Rectal temperature
Blood pressures
EKG (scalar and vector)

Audiograms
Ear conduction [I]
Bone density [III]
Precordial doppler[a]
Long bone radiographs

Urine

24 hour volume, Ca, P04, Na, K, hydroxy proline, creatinine, urea, 17-hydroxysteroids, osmolarity, protein, ketone, sugar, blood, microscopic cells.

Blood

RBC, WBC, and differential, PCV, Hb, MCV, MCH, MCHC, reticulocytes, platelets, Ca ionic and total, Na, K, Cl, osmolarity, LDH, SGPT, SGOT, CPK, alkaline phosphatase, bilirubin, creatinine, glucose, BUN, protein total and fractions, albumin, haptoglobin, T_3, T_4, T_7, and lipoproteins on SHAD I only.

Oral Physiology

Parotid fluid (stimulated)

Microbiology

Aerobacteriology, skin, oral, nasal, potable water, mechanical environment

*[ ] Indicates SHAD dive in which a particular study was not employed
[a] employed in pre-SHAD I

A typical day began at 0600 and ended at 2300. In SHAD I and II periodic two-hour rest periods were scheduled each morning and afternoon. Excursion dives and lengthy testing regimens (for example, exercise tolerance) interrupted the rest periods. In SHAD III, the eight-hour excursions included a brief rest period. Four-hour rest and recreational periods were scheduled on most evenings.

All excursions were conducted without decompression prior to returning to the storage depth. The individual excursion profiles, surface intervals, and decompression times are shown in Tables 19 through 22.

TABLE 19

Pre-SHAD I dive profile

Dive Day	Elapsed Time (min)	Event	Depth (fswg)	Time at Depth (min)	Time of Day hr:min:sec	Comment
1	0.0	L	0		12:35:00	
1	1.7	R	50			
3	2641.7	L	50	2640	08:48:40	Travel 6 min/ft
3	2821.7	L	20			Travel 15 min/ft
3	2971.7	L	10			Travel 20 min/ft
3	3071.7	L	5			Travel 30 min/ft
3	3215.4	R	0		18:22:20	*

Total time at depth: 1 day, 20 hrs, 12 min.
Total decompression time: 9 hrs, 33 min, 40 sec.
* Both divers exited chamber with minor knee pains.

3	3433.1	L	0		22:00:00	Treatment table 6.**
3	3435.1	R	60		22:02:00	**
3	3510.1	L	60		23:17:00	**
3	3540.1	R	30		23:47:00	**
4	3690.1	L	30		02:17:00	**
4	3720.3	R	0		02:47:13	

** Intermittent 100% oxygen, air breathing as per table instructions. Both divers exited chamber with mild residual pain and difficult respiration.

The pre-SHAD I decompression regimen was accomplished through sequential pressure decreases of three inches of sea water while the compression regimen for the remaining three dives was accomplished by sequential pressure decreases of six inches of sea water (simulated). The first dive in this series, pre-SHAD I, was designed primarily as a chamber habitability evaluation and did not involve as extensive a biomedical evaluation program as was subsequently employed.

TABLE 20

SHAD I dive profile

Dive Day	Elapsed Time (min)	Event	Depth (fswg)	Time at Depth (min)	Time of Day hr:min:sec	Comment
1	0.0	L	0		11:39:20	
1	1.5	R	50			
9	11432.9	L	50		10:11:16	
9	11435.5	R	200			
9	11453.5	L	200	18.0		
9	11458.6	R	50		10:36:54	
12	15754	L	50		10:16:22	
12	15757.2	R	235			
12	15763.1	L	235	5.9		
12	15769.4	R	50		10:31:46	
14	18618	L	50		10:12:24	
14	18621.2	R	235			
14	18627.1	L	235	5.9		
14	18633.3	R	50		10:30:42	
16	21807.5	L	50		15:06:51	
16	21809.6	R	235			
16	21815.6	L	235	6.0		
16	21821.9	R	50		15:21:15	
17	22951.5	L	50		10:10:53	S.I. = 18:49:38
17	22954.0	R	200			
17	22972.0	L	200	18.0		
17	22977.2	R	50		10:36:35	
19	26126.2	L	50		15:05:30	
19	26128.8	R	200			
19	26147.5	L	200	18.7		
19	26152.7	R	50		15:32:30	
20	28051.2	L	50		23:10:32	
20	28058.8	R	200			
20	28076.8	L	200	18.0		
20	28082.6	R	50		23:41:56	
21	28723.2	L	50		10:22:33	S.I. = 10:40:37
21	28725.1	R	150			
21	28767.9	L	150	42.8		
21	28771.4	R	50		11:10:45	
22	30155.5	L	50		10:14:54	S.I. = 23:04:09
22	30158.4	R	5			
22	30189.1	L	5	30.7		
22	30190.1	R	50		10:49:30	
23	31890.6	L	50		15:09:54	S.I. = 28:20:14
23	31892.3	R	150	43.0		
23	31935.3	L	150			
23	31938.7	R	50		15:58:00	

TABLE 20 (cont.)

SHAD I dive profile

Dive Day	Elapsed Time (min)	Event	Depth (fswg)	Time at Depth (min)	Time of Day hr:min:sec	Comment
25	34770.6	L	50		15:09:55	
25	34772.6	R	15			
25	34829.6	L	15	57.0		
25	34830.2	R	50		16:09:31	
25	35248.4	L	50		23:07:45	S.I. = 6:58:14
25	35250.1	R	150			
25	35298.9	L	150	48.8		
25	35303.2	R	50		Day 26 00:02:33	
26	35917.3	L	50		10:16:40	S.I. = 10:14:07
26	35919.0	R	150			
26	35962.0	L	150	43.0		
26	35965.4	R	50		11:02:13	
26	36211.9	L	50		15:08:44	S.I. = 4:06:31
26	36212.3	R	75			
26	36272.3	L	75	60.0		
26	36273.5	R	50		16:10:20	
27	37358.1	L	50		10:14:54	S.I. = 18:04:34
27	37359.0	R	100			
27	37417.3	L	100	58.3		
27	37419.1	R	50		11:15:54	
27	38138.0	L	50		23:14:50	S.I. = 11:58:56
27	38139.8	R	15			
27	38194.0	L	15	54.2		
27	38195.3	R	50		Day 28 00:12:08	
28	38869.2	L	50		11:25:03	S.I. = 11:13:55
28	38872.1	R	5			
28	38902.7	L	5	30.6		
28	38903.5	R	50		11:59:21	
28	39150.0	L	50		16:05:50	S.I. = 4:06:29
28	39152.6	R	200			
28	39170.6	L	200	18.0		
28	39175.6	R	50		16:31:26	
30	41610.2	L	50	28 days 21:30:12	09:06:00	Start decompression Travel rate 6 min/fsw
30	41700.2	L	35			Travel rate 15 min/fsw
30	42075.2	L	10			Travel rate 33 min/fsw
30	42240.2	L	5			Travel rate 36 min/fsw
30	42420.2	R	0		22:36:00	

Total time at depth: 28 days, 21 hrs, 30 min, 12 sec.
Total decompression time: 13 hrs, 30 min.

TABLE 21

SHAD II dive profile

Dive Day	Elapsed Time (min)	Event	Depth (fswg)	Time at Depth (min)	Time of Day hr:min:sec	Comment
1	0.0	L	0		14:00:00	
1	2.3	R	60			
8	9852.2	L	60		10:12:13	
8	9853.4	R	100			
8	9912.9	L	100	59.5		
8	9915.2	R	60		11:15:13	
12	15601.0	L	60		10:01:00	
12	15601.8	R	100			
12	15661.8	L	100	60.0		
12	15663.3	R	60		11:03:13	
14	18780.0	L	60		15:00:00	
14	18780.9	R	100			
14	18840.7	L	100	59.8		
14	18841.9	R	60		16:01:55	
16	21360.0	L	60		10:00:00	
16	21361.6	R	150			
16	21421.5	L	150	59.9		
16	21424.5	R	60		11:04:31	
17	23235.0	L	60		17:15:00	
17	23238.4	R	200			
17	23258.4	L	200	20.0		
17	23263.1	R	60		17:43:16	
19	25695.0	L	60		10:15:00	
19	25698.3	R	250			
19	25704.1	L	250	5.8		
19	25710.6	R	60		10:30:40	
20	27120.0	L	60		10:00:00	S.I. = 23:29:10
20	27123.6	R	5			
20	27144.9	L	5	21.3		
20	27145.8	R	60		10:25:46	
22	30010.0	L	60		10:10:00	
22	30012.3	R	15			
22	30043.5	L	15	31.2		
22	30044.3	R	60		10:44:21	
22	30300.0	L	60		15:00:00	S.I. = 4:15:39
22	30302.6	R	200			
22	30322.5	L	200	19.9		
22	30327.3	R	60		15:27:24	
23	31440.0	L	60		10:00:00	S.I. = 18:32:36
23	31441.5	R	150			
23	31501.5	L	150	60.0		
23	31504.5	R	60		11:04:33	
23	31739.9	L	60		15:00:00	S.I. = 3:55:27

TABLE 21 (cont.)

SHAD II dive profile

Dive Day	Elapsed Time (min)	Event	Depth (fswg)	Time at Depth (min)	Time of Day hr:min:sec	Comment
23	31740.6	R	100			
23	31800.6	L	100	60.0		
23	31802.0	R	60		16:02:06	
24	32885.4	L	60		10:05:31	S.I. = 18:03:25
24	32886.1	R	100			
24	32946.0	L	100	59.9		
24	32947.3	R	60		11:07:30	
24	33179.8	L	60		15:00:00	S.I. = 3:52:30
24	33182.0	R	15			
24	33213.3	L	15	31.3		
24	33214.0	R	60		15:34:17	
25	34320.0	L	60		10:00:00	S.I. = 18:25:43
25	34323.4	R	5			
25	34344.9	L	5	21.5		
25	34345.9	R	60		10:25:53	
25	35100.0	L	60		23:00:00	S.I. = 12:34:07
25	35102.3	R	200			
25	35122.3	L	200	20.0		
25	35126.9	R	60			
28	38520.0	L	60	26 days 18 hrs.	08:00:00	Start decompression Travel rate 10 min/ft
28	38670.5	L	45			Travel rate 15 min/ft
28	39069.0	L	19			Travel rate 33 min/ft
28	39300.0	R	12		21:00:00	Sleep hold
29	39789.0	L	12	489.0	05:09:00	Travel rate 33 min/ft
29	4002.0	L	5			Travel rate 36 min/ft
29	40200.1	R	0		12:00:07	

Total time at depth: 26 days, 18 hrs.
Total decompression time: 1 day, 4 hrs, .07 sec.

TABLE 22

SHAD III dive profile

Dive Day	Elapsed Time (min)	Event	Depth (fswg)	Time at Depth (min)	Time of Day hr:min:sec	Comment
1	0.0	L	0		10:42:00	
1	1.7	R	50			
2	1403.0	L	50		10:05:02	
2	1404.8	R	100			
2	1883.0	L	100	478.2		Travel at 2 ft/min
2	1908.0	R	50		18:30:00	
3	2838.0	L	50		10:00:03	S.I. = 15:30:03
3	2839.5	R	100			
3	3317.9	L	100	478.4		Travel at 2.5 ft/min
3	3337.9	R	50		18:20:00	
4	4278.0	L	50		10:00:00	S.I. = 15:40:00
4	4279.6	R	100			
4	4758.0	L	100	478.4		Travel at 3.3 ft/min
4	4773.0	R	50		18:15:03	
5	5718.0	L	50		10:00:00	S.I. = 15:44:57
5	5719.7	R	100			
5	6197.9	L	100	478.2		Travel at 5 ft/min
5	6208.5	R	50		18:10:34	
6	7158.1	L	50		10:00:05	S.I. = 15:49:31
6	7159.6	R	100			
6	7638.0	L	100	478.4		Travel at 16.7 ft/min
6	7641.0	R	50		18:05:03	
7	8598.0	L	50		10:00:01	S.I. = 15:54:58
7	8599.8	R	100			
7	9078.0	L	100	478.2		Travel at 30 ft/min
7	9079.7	R	50		18:01:43	
8	10020.0	L	50	6 days 23 hrs	09:42:00	Start decompression Travel at 10 min/ft
8	10170.0	L	35			Travel at 15 min/ft
8	10395.0	L	20			Travel at 54 min/ft
8	10537.2		18			Holding
8	10553.6	L	18		18:35:36	PP pain only bends
	10554.2	R	28			
8	10580.0		28		19:02:00	On O_2
8	10590.0		28		19:12:03	Off O_2
8	10595.0		28		19:17:00	On O_2
8	10605.0		28		19:27:00	Off O_2
8	10610.0		28		19:32:00	On O_2
8	10620.0		28		19:42:00	Off O_2
8	10625.0		28		19:47:00	On O_2
8	10635.0		28		19:57:00	Off O_2
8	10658.0	L	28		20:20:00	Travel at 54 min/ft
8	10848.2	R	24		23:30:11	Sleep hold

TABLE 22 (cont.)

SHAD III dive profile

Dive Day	Elapsed Time (min)	Event	Depth (fswg)	Time at Depth (min)	Time of Day hr:min:sec	Comment
9	11239.0	L	24		06:00:00	Travel at 54 min/ft
9	12183.0	R	6		21:45:00	Sleep hold
10	12723.0	L	6		06:45:00	Travel at 12.5 min/ft
10	12798.3	R	0		08:00:20	

Total time at depth: 6 days, 23 hrs.
Total decompression time: 1 day, 22 hrs, 18 min, 20 sec.

The decompression procedures used in the SHAD program were based on those used in NOAA OPS I and II, with modifications for the air environment. The decompression schedules employed in SHAD II and III were derived in part, at the NSMRL and may be seen in Tables 21 and 22 respectively.

Results:

A total of 3,516 man-hours of air saturation were safely completed. Eight ascending and 31 descending excursions were conducted between the depths of 5 and 250 feet.

Significant, environmentally-related medical changes were not observed during the saturation periods. A minor external otitis was observed during SHAD I and II, which responded to routine treatment. The health problems, both medical and dental, that did occur were typical of those normally encountered at the surface.

Significant forced vital capacity reductions were not observed during pre-SHAD I, SHAD I, or SHAD II. During SHAD III, however, one diver had a reduction in forced vital capacity following the fourth, fifth and sixth excursion dives. Near-baseline level was reached during the intervening residence periods at 50 fsw. The maximum reduction in vital capacity was 9.6%. Predicated on current procedures, the cumulative oxygen dose of SHAD II exceeded the limits required to produce a 10% vital capacity decrease by more than 800%.

Three of the nine divers had symptoms of decompression sickness. In each case, a combination of recompression and pure oxygen breathing was employed in the therapeutic treatment and on each occasion, changes indicative of oxygen toxicity were observed. The US Navy Standard Treatment Table 6 was used for the pre-SHAD I divers resulting in symptoms of both pre-convulsive

central nervous system disorder and pulmonary toxicity. After using the treatment procedure for SHAD III (see Table 22), a 24% decrease in forced vital capacity was measured in one diver. However, it returned to the baseline level during the remainder of the decompression regimen.

Although there were no symptoms of oxygen toxicity at storage depth, the consistent observation of such symptoms and/or related changes during bends treatment cannot be overlooked and must be taken into account when planning air saturation missions. These changes suggest that some alteration occurred in the divers that precluded their ability to accommodate to what would normally be a routine treatment procedure employing 100% oxygen. When such an alteration occurred, it did so within two days (pre-SHAD I) and was not observable with the techniques employed in the SHAD program.

Ascending excursions involving a maximum pressure differential of 1.67 atm. (55 fsw) were evaluated. They were used in both non-repetitive and repetitive combinations with descending excursions. No symptoms of decompression sickness occurred except for skin itching that is commonly found in dry chamber dives. Circulating gas bubbles were occasionally detected at the end of the excursion periods. These did not occur, however, after the repetitive descending excursions that followed the ascending excursions.

Measurements indicated significant reductions in red blood cell mass in both SHAD I and II. The decline, initially noted on about the 10th day, continued until the dive was completed. Maximum reductions of red blood cell mass of 12.5% in SHAD I and 19.3% in SHAD II were observed during the period immediately after surfacing, but subsequently returned to baseline levels in each diver. No significant alterations were determined in either the blood or urine chemistries or biochemistries, although a total data analysis has not been completed.

Visual fields, visual acuity, and EEG did not exhibit significant changes in SHAD I or II (Kinney *et al.* 1974). Retinal arteries and veins constricted during the first week of each dive and remained so throughout each exposure. Visual evoked responses and various tests in the human factors test battery demonstrated the anticipated changes during the deeper excursion dives of SHAD I and II. Data analysis for SHAD III has not been completed.

While narcosis was evident during the deeper excursions, it did not limit the diver's effectiveness with regard to the completion of assigned tasks. The results of the human factors test battery suggested some accommodation to narcosis during the deeper excursions as the dives progressed.

The utilization of an arbitrary 60-minute excursion time limit in SHAD I and II precluded the testing of maximum excursion times at depths equal to or less than 100 fsw. SHAD III, however, clearly demostrated the possibility of a full eight-hour working day at a depth of 100 fsw, operating from a storage depth of 50 fsw. Data analysis has not been completed with respect to the general applicability of the repetitive dive sequences used in the SHAD program.

Summary:

The SHAD program has further documented the feasibility of mans' residence in air at 50 and 60 fsw for extended periods as well as the availability of an air excursion matrix ranging from 5 to 250 fsw. Significant insight into the ranges of oxygen partial pressures to which man can accommodate has also been acquired. The higher oxygen partial pressures experienced while at storage depth, however, seem to be a potential hazard if oxygen treatment is necessary. Further work needs to be done to better understand and reduce this hazard.

The SHAD results have provided additional information which should enhance the utilization of air saturation procedures in a multitude of diving and tunneling endeavors.

IV-C SCORE (Scientific Cooperative Operational Research Expedition)

PHASE I

Introduction:

The conclusions of the NOAA OPS I and II experiments indicated that residence in a normoxic nitrogen environment at increased ambient pressures for periods of one week does not appear to cause a significant degradation of cognitive and psychomotor function. On the contrary, there seemed to be an adaptation to nitrogen narcosis which extended to the deeper excursion dives. Cognitive and psychomotor performance during compressed air excursions from saturation was significantly improved over performance during dives to the same depths from the surface. The SHAD program further verified these conclusions using divers saturated in an air environment at depths of 50 and 60 fsw. In each of these programs, however, vertical excursions were made such that decompression was not required prior to returning to the storage depth.

In order to increase useful bottom time as well as further verifying these earlier studies, excursion profiles were developed which require decompression prior to returning to storage depth. Evaluation of these new excursion profiles was carried out in the laboratory and in the open-sea along with further tests to determine whether there was any impairment of cognitive, psychomotor, or physiological functions.

Purpose:

To saturate divers on air at a depth of 60 fsw and to make excursions to depths of 200, 250 and 300 fsw for periods of one hour using profiles which include decompression prior to returning to the 60-foot storage depth.

Location: F. G. Hall Laboratory for Environmental Research, Duke University, Durham, North Carolina

Date: January 27 - February 10, 1975

Duration: 14 days (5 days saturation)

Saturation Depth: 60 feet

Breathing Gas: Storage - air; excursions - air

Subjects: 8

Facility: Duke University Laboratory

The core facility, a multichamber environmental complex with supporting laboratory space, occupies a three-story area of the Medical Center (Fig. 4).

For these experiments the hyperbaric part of the complex used was a cylindrical chamber 36 feet in length, with an internal diameter of 10 feet 6 inches, divided into two compartments, spherical lock, and a treatment compartment (marked C in Fig. 4). The wet chamber, D, is immediately beneath the sphere, C.

All compartments have multiple windows, access plates for penetrations of biomedical sensors, communications systems, and independent capabilities for pressurization and ventilation. The five compartments on the ground floor level have internal gas circulation systems for control of humidity and temperature. These systems have been modified in the deep diving complex for removal of carbon dioxide as well. Fire control systems are based on inundation with water and pass-through locks for introduction or removal of materials. The five compartments on the ground floor are pressurized, ventilated, and controlled in all respects from a console. Controls are automatic pneumatic, manual pneumatic, and manual. Communication between console operators and occupants of the chambers utilizes headset-microphone systems, a microphone-loud speaker system, television and chamber windows.

Divers:

Two teams were selected of four men each, with a fifth as a standby in the event of illness. One experienced Duke Chamber diver was selected from each group to make dives in the wet chamber. All divers were experienced and ranged in age from 26-40. Complete medical examinations and long-bone x-rays, respiratory function tests, EEG, EKG, auditory, vestibular and visual tests were made to ensure the health and safety of the subjects.

Procedure:

Baseline data were collected from all subjects for one week prior to the saturation dive. These data included:

Performance tests

1) Arithmetic test. Two figure by one figure multiplication (e.g.
6 68x9 =) (testing time = 1 min).

2) Ball bearing test. Picking up ball bearings with tweezers and placing them in a tube of the same diameter (testing time = 1 min).

3) Signs and symptoms questionnaire.

4) Digit span forward. Numbers are read out which the subject has to repeat forwards. The numbers increase in length one at a time until the subject makes an error (testing time = 3 min).

5) Time estimation. The subject is required to estimate the passage of randomly selected times ranging from 6 to 24 seconds (testing time = 3 min).

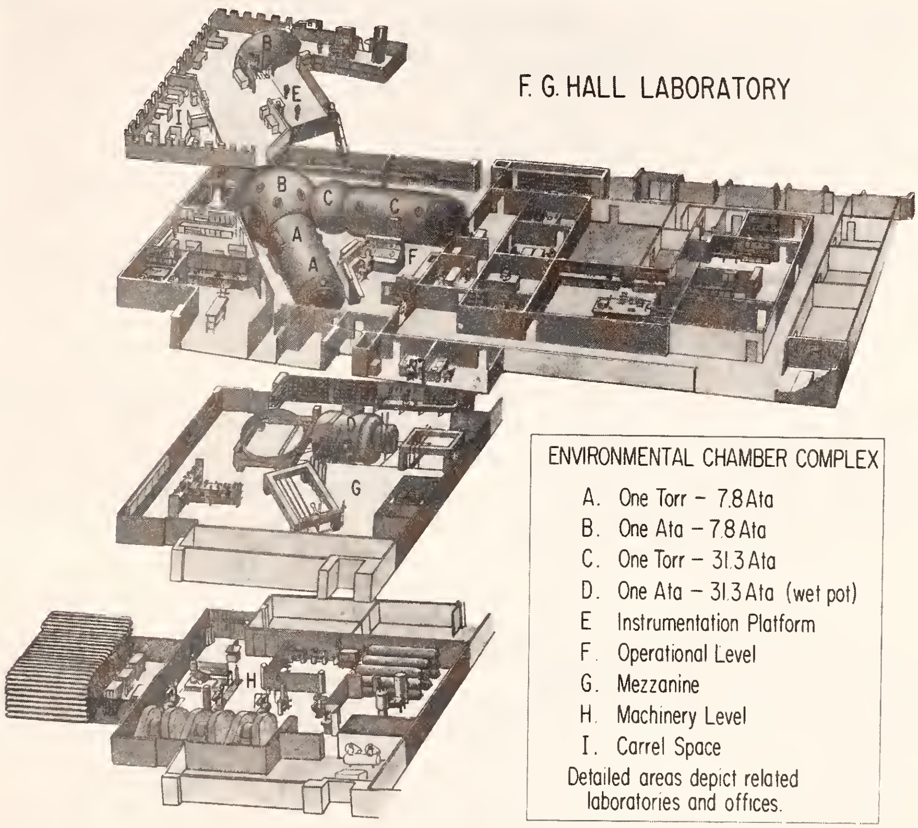

Fig. 4. Duke University experimental diving facility used for SCORE (Phase I)

Hematology and Blood Chemistry

The reduction of circulating platelet count in divers decompressed from a hyperbaric environment has been reported by several investigators and was discussed in a recent review (Philp 1974). It has since been confirmed by other investigators (Valeri, Feingold, Zuroulis, Sphar, and Adams 1974). Information concerning this phenomenon as it relates to saturation diving is, however, scanty. The suggestion has been made, based on the results of animal experiments, that platelets adhere to, and aggregate around, intravascular bubbles and subsequently disappear from the circulation either because of a shortened life-span or because they become trapped as minute thrombi in the microcirculation. In order to better understand this phenomena further, studies were made during the SCORE program.

Blood Samples

Twenty-ml blood samples from a forearm vein occluded with a wide tourniquet were collected into disposable plastic syringes using disposable 20-gauge needles. The blood samples were immediately distributed into test tubes containing the appropriate anticoagulant. To minimize blood loss, not all divers were sampled on all occasions. All ten subjects were sampled on Day 1 and before the 200-fsw bounce dive (Day 2); five after the 250-fsw bounce dive (Day 3); four before the 300-fsw bounce dive (Day 4); ten before the saturation dive (Day 6); four shortly after completion of the last (300-fsw) excursion dive; four after another 24 hours (Day 10); and eight after surfacing from the excursion dive (Day 11). Seven were sampled 24 hours later and six were sampled 48 hours later. Four of these six had participated in a final 300-fsw bounce dive the previous day.

Hematology

Red-cell counts, white-cell counts, hemoglobin concentration, packed-cell volume (PCV) and corrected sedimentation rate (CSR) were conducted by the diagnostic service of Duke University Medical Center; all counts were performed electronically. For purposes of comparison, red blood cells were counted in a hemocytometer with a microscope.

Blood Chemistry

The activities of lactic dehydrogenase (LDH), creatine phosphokinase (CPK), alkaline phosphatase (ALP), glutamic-oxaloacetic transaminase (GOT) and glumatic-pyruvic transminase (GPT) were measured in plasma by the methods described previously (Philp, Freeman, Francey, and Ackles 1974).

Bubble Detection

Additional data were obtained using a Doppler bubble detector with an over-the-heart sensor during decompression following excursions.

The subjects started the performance tests at the surface and continued regular and frequent practice to reduce the learning effect as far as possible within the time available.

Control studies were performed at depths of 200, 250, and 300 fsw during which the subjects descended from the surface and remained for 15 minutes while taking performance tests. Further control data were obtained upon reaching the 60-foot saturation depth. During all excursions, performance tests were administered and blood samples obtained. A 300-foot dive was conducted the day following the decompression to surface as a post-dive control. Experiments to test for possible adaptation to increased nitrogen partial pressures were run prior to and post dive as well as at the saturation depth and during excursions.

Three excursion profiles were provided by Tarrytown Labs to Duke University for testing. As a safety precaution, an additional five profiles (abort tables), with shorter bottom times, also were provided.

The following criteria were used in the computation of all profiles:

1. Breathing gas: air (20 percent oxygen, balance nitrogen).

2. Saturation level: 65 fsw, divers returning to 60 fsw.

3. Instantaneous compression to excursion depth.

4. Excursion calculated at a depth 5 fsw greater than that listed for the profile; i.e., 255 fsw for 250 fsw excursion.

5. Initial ascent rate of 30 fsw per minute.

6. Rate of ascent between stops of 10 fsw per minute.

7. Decompression stop time rounded to next whole minute.

8. All calculations based on the "smoothed" constraint matrix.

Table 23 shows the excursion decompression profiles provided.

The rationale used for the selection of a saturation level of 65 fsw was that these tables would be used in the field where repetitive diving over the course of several days would be done without the backup of a computer or residual nitrogen tables. The return to 60 fsw was dictated by the depth of the habitat. In using a five fsw greater excursion depth the same reasoning was used as in the original work; that is, all depth gauges are not equal, so it is better to allow for possible error.

The decompression schedule used for return to the surface is shown in Table 24. This table is based on the assumption that the compartment with the longest half-time is the controlling compartment for a saturation de-

TABLE 23

Excursion decompression profiles for a 60-fsw habitat

Excursion Depth (fsw)	Excursion Time (min)	Stop time (min) / Stop depth (fsw)									Total Ascent Time*
		150	140	130	120	110	100	90	80	70	
200	30									$3\frac{1}{3}$	9
	60							$5\frac{1}{3}$	4	3	19
250	30							$6\frac{2}{3}$	4	3	22
	60				$\frac{2}{3}$	3	7	6	9	9	45
300	15							1	4	3	18
	30					$1\frac{2}{3}$	7	6	4	4	34
	45			$2\frac{1}{3}$	3	3	7	7	9	10	55
	60	2	3	3	3	5	10	10	9	44	103

* Ascent time to first stop was 30 fsw/min
Ascent time between stops was 10 fsw/min

compression. An initial ascent at six minutes per fsw was scheduled to the depth at which the calculated inert gas partial pressure loading for the compartment reached the value specified in the constraint matrix for that depth. Decompression then proceeded at the rate required to clear the next 1/4 fsw shallower. The rate was approximated over one fsw intervals and in time blocks of whole minutes per fsw. Air was the only breathing gas used for this decompression.

The saturation at 60 fsw began on February 2, 1975. The excursions were carried out in accordance with the following schedule:

Day 1 1800 Compress to 60 fsw using air.

Day 2 0927 Team A compresses to 200 ft for a 60 min bottom time.

1502 Team B compresses to 200 ft for a 60 min bottom time.

TABLE 24

Air decompression from air saturation at 60 fsw

Depth (Ft)	Rate of Decompression	Time (min)
60 to 30	6 min/ft	180
30 to 28	22 min/ft	44
28 to 26	23 min/ft	46
26 to 24	24 min/ft	48
24 to 22	25 min/ft	50
22 to 20	26 min/ft	52
20 to 18	27 min/ft	54
18 to 16	28 min/ft	56
16 to 13	29 min/ft	87
13 to 10	30 min/ft	90
10 to 8	31 min/ft	62
8 to 6	32 min/ft	64
6 to 4	33 min/ft	66
4 to 2	34 min/ft	68
Time at 1 foot	68 min	68
	Total	17 hrs. 15 min

Day 3	0912	Team A compresses to 250 ft for a 60 min bottom time.
	1502	Team B compresses to 250 ft for a 60 min bottom time.
Day 4	0911	Team A compresses to 300 ft for a 60 min bottom time.
	1500	Team B compresses to 300 ft for a 57.4 min bottom time.
Day 5	2000	Begin decompression from 60 ft to the surface.
Day 6	1315	Subjects surface.

Results:

Two-Hundred Foot Excursions: No problems attributable to bends were noted. One subject reported pain in the left elbow during the excursion. Symptoms were exacerbated by decompression. The pain became progressively worse over the course of the three hours after arrival at storage depth prior to his reporting it to the medical officer. He was treated with oxygen and recompressed to 100 fsw. When no relief was reported, subjects were decompressed to storage depth. The diagnosis was made that this subject had bursitis, a pre-existing condition in his other elbow. Further treatment consisted of hot towels for the elbow.

Two-Hundred Fifty Foot Excursions: On February 4, 1975 subject HT reported bilateral numbness of his fingers and backs of hands following the morning excursion to 250 fsw at return to 60 fsw, plus 10 minutes. Preliminary diagnosis was a vasoconstrictive phenomenon due to the elevated partial pressure of oxygen. To confirm the preliminary diagnosis, the subject was asked to breathe one cycle of 25-minute duration, at 60 fsw, after which he reported no exacerbation or relief of symptoms. Following immersion of his hands in warm water, temporary relief was obtained. Final diagnosis was that subject HT was susceptible to the effect of elevated oxygen partial pressures, and that the symptoms reported were indicative of oxygen toxicity.

No symptoms of decompression sickness were reported following the 250-fsw excursions. Doppler bubble sounds were heard on subjects HT and DS, the two subjects exposed to the treatment regimen the previous evening. There were no bubbles detected in the other six subjects during the periods in which they were monitored.

Three-Hundred Foot Excursions: The 300 fsw excursions were conducted on February 5. Subject HT was not allowed to participate in the morning excursion as he reported the tips of his fingers were still numb. Following a report that the symptoms had cleared, he was added to the afternoon excursion.

The morning excursion proceeded without incident, but at 54 minutes into the afternoon excursion, subject HT went into convulsions. Following

completion of the convulsions and resumption of a normal breathing pattern, decompression to storage depth began (at 57.4 minutes into the excursion) and proceeded without incident. Ten minutes after return to 60 fsw, subject WM reported bilateral deep upper arm (triceps) pain. Ten minutes later, at 1800, WM and tender FR (JR was locked in from the surface) were compressed to 100 fsw. On arrival, WM began breathing 50 percent oxygen in nitrogen. After 10 minutes, the subject was switched to 50 percent oxygen in helium, for the remainder of the 25-minute treatment. After the treatment cycle, during which symptoms were relieved, subject WM was switched to a breathing mixture of 20 percent oxygen in helium and was decompressed on the 300-foot for 60-minute excursion decompression profile from the 100 fsw level.

At 70 fsw, WM reported numbness of fingers and was asked to breathe chamber atmosphere (air) for the remaining 13 minutes of the decompression profile. After the initial switch to heliox, WM experienced urticaria which cleared as treatment progressed. On arrival, he said "Skin feels tight," over the left aspect of the upper arm -- a condition which continued through surfacing.

Following the treatment of WM (2000 hours), subject HT went into shock (BP 80/40, pulse 80 and weak), and was rapidly administered 200 cc of Lactated Ringer's solution, followed by an additional 1000 cc over the next three hours. Over the next seven hours, 1000 cc of D5W 5 percent dextrose in water were administered and then 1000 cc of Lactated Ringer's at 15 drops per minute to keep the IV open. It was felt that this was a continuation of the oxygen-toxicity problem he had been experiencing.

Performance Tests

The results of the performance tests are summarized in Table 25. An analysis of the data determined that the standard errors of the mean were both variable and high, in some cases exceeding the percentage changes themselves. Thus, in spite of the fact that considerable practice was offered prior to the dive, the variability of results was high. Such variation could be attributed to many factors in addition to depth and inert gas narcosis such as fatigue, motivation, learning rate, etc.

Recognizing the dangers of averaging percentages, it is apparent from Table 25 that the poorest performance was elicited during the presaturation bounce dives. The slight improvement shown during tests at 60 fsw saturation are minor and may simply reflect continued learning. The results obtained during excursions show considerable decrement during the 300-foot excursions (and post-saturation bounce dives) compared to those data obtained at 200 and 250 fsw. There appears to be some improvement in performance during the 200- and 250-foot excursions compared to the initial bounce dives to those same depths. Some learning is still present however, as can be seen by comparison of the pre- and post-saturation dives to 300 fsw. Thus, the improvement in the excursion results compared to the bounce dives may be a function of learning rather than a physiological adaptation to narcosis.

TABLE 25

Summary of SCORE phase I performance tests*

Depth (ft)	Presaturation Dive Bounce	Presaturation Dive Post Bounce	60 ft** Saturation	Excursions 0-20 min	Excursions 40-60 min	Post Excursion at 60 (ft)	Post Saturation at Surface	300 ft Bounce Dive	Post 300 ft Bounce Dive at Surface
200									
Math	-15	+7	+3	-22	-20	-6	-	-	-
Ball Bearing	-13	+2	+10	+13	+6	+14	-	-	-
Digit Span	-22	+8	+3	-12	-11	+3	-	-	-
Time Estim.	-6	0	-3	-2	-3	-1	-	-	-
$\overline{X}$	-14.0	+4.2	+3.2	-6.2	-7.0	+2.5	-	-	-
250									
Math	-36	-9	-	-5	-10	+6	-	-	-
Ball Bearing	-16	+4	-	-7	-7	+9	-	-	-
Digit Span	-21	0	-	-9	-14	-2	-	-	-
Time Estim.	-1	+4	-	-5	-4	-1	-	-	-
$\overline{X}$	-18.5	-0.2	-	-6.5	-8.8	+3.50	-	-	-
300									
Math	-40	-1	-	-30	-29	-	+5	-22	-4
Ball Bearing	-19	+10	-	-19	-15	-7	-5	-6	-4
Digit Span	-21	+14	-	-11	-4	+9	-6	-15	-2
Time Estim.	-13	-6	-	-6	-8	0	-9	-15	-1
$\overline{X}$	-23.2	+4.2	-	-16.5	-14.0	+0.5	-3.8	-14.5	-2.8
Grand $\overline{X}$ %	-18.6	+2.8	+3.2	-9.6	-9.9	+3	-3.8	-14.5	-2.8

* Numbers are per cent changes in performance compared to control predive data

** Data obtained at beginning of 60-foot saturation

Observations of the behavior of the two groups also indicated little or no adaptation during the deep excursion dives as compared to bounce dives. At 300 fsw, the subjects were obviously euphoric (in group B especially), with considerable hilarity, confusion, and slow-witted reactions to instructions from the outside control crew. When the oxygen convulsion occurred at 300 fsw, for example, the experienced inside controller was urging immediate decompression, although he is normally well aware of the dangers of decompressing an individual during a convulsion.

Vital Capacity

Measurements of vital capacity were made during the saturation dive, at pre- and post-excursion periods, and pre- and post-saturation to check for evidence of pulmonary oxygen toxicity (Clark and Lambertsen 1971, Widel *et al.* 1974). The results shown in Table 26 indicate a marked decrease in vital capacity in two of the subjects based on 10% being defined as a significant decrease.

TABLE 26

Results of vital capacity measurements

	200 ft		250 ft		300 ft		Post	
Subjects	Pre	Post	Pre	Post	Pre	Post	Saturation	
H.T.	5.97	5.98	6.21	6.02	6.2	5.0**	5.65	(-5.4%)
T.B.	4.76	4.62	4.00	4.39	4.0	4.0	4.01	(-15.8%)
R.J.	5.60	5.41	5.60	5.50	5.3	5.35	5.5	(-0.9%)
A.O.	5.03	5.88	6.19	7.60	4.6	7.6	4.2	(-20.8%)
D.S.	4.00	4.22	4.40	4.25	4.51	4.4	4.2	(+5.0%)
M.B.	6.70	6.67	6.68	6.61	6.80	6.65	6.65	(-0.7%)
J.H.	6.00	5.71	5.95	5.85	5.85	5.42	5.91	(01.5%)
W.M.	5.81	5.82	5.40	5.40	4.90	5.59	5.30	(-8.8%)
Total	44.14	44.31	44.43	45.62	42.16	44.01	41.47	
	--	+0.4%*	+0.1%*	+3.4%*	-4.5%*	-0.3%*	-0.06%*	

* % change from 200 ft. pre-saturation dive

** Subject H.T. not feeling well during this period

Considering the decrease in vital capacity, and the other signs of oxygen toxicity described earlier, such as the overt convulsion and the numbness of fingers, it must be inferred that saturation-excursion procedures, as performed in the present study, carry a definite risk of both pulmonary and central nervous system oxygen toxicity.

Hematology and Blood Chemistry

Platelet studies

There was a significant loss of platelets after the 250-fsw bounce dive with a slight recovery prior to saturation. The lowest counts were obtained following completion of all the excursion dives from saturation depth at which point the mean percent loss was 28.0 ± 6.18(SEM) ($P < .02$). After surfacing from the saturation depth, the counts were still significantly depressed. There was a trend toward recovery thereafter except for the groups which performed the 300-fsw bounce dive in which there was a further (15.0% ± 5.48 SEM) reduction in count. Platelet aggregation studies indicated that the fall in circulating platelet count was accompanied by a marked and statistically significant reduction in sensitivity of platelets ADP-induced aggregation. This trend persisted in the group which did the post-saturation 300-fsw bounce dive.

Hematology

Red-cell counts (performed electronically) and PCV showed evidence of a significant anemic response which was most pronounced in the sample collected at saturation depth following completion of all the excursion dives. Visual red-cell counts and hemoglobin concentration showed similar but not statistically significant trends. White-cell counts were noticeably and significantly increased after the 250-fsw bounce dive and prior to the saturation dive. No significant changes in corrected sedimentation rate were observed.

Blood Chemistry

In the majority of divers, changes in plasma enzymes activities were minimal. However, two subjects showed relatively large increases in certain plasma enzymes. One demonstrated elevated LDH and CPK levels immediately following the pre-saturation bounce dive to 250 fsw. CPK continued to increase to a maximum of 22 times control value post-saturation, followed by a decrease 24 hours post-saturation. The maximum enzyme changes occurred after he suffered from apparent oxygen-induced convulsions following the 300-fsw excursion dive.

A second subject exhibited elevations in LDH, GOT, GPT after the 300-fsw excursion. These enzyme activities reached a maximum of +82.8%, +364.1%, and +1177%, respectively, immediately post-saturation.

Decompression:

The decompression to the surface began at 2000 hours, 6 February, and continued until 1315 hours, 7 February, and was uneventful. Doppler bubbles were heard on several of the divers during the ascent to the first stage, which cleared after the rate slowed. One subject had Doppler bubbles after surfacing, but did not experience symptoms of decompression sickness.

Summary

It is concluded that, so far as the present study is concerned, there is insufficient evidence to support an adaptation to nitrogen narcosis in compressed air saturation-excursion diving. Based on the risk of oxygen convulsions, it was recommended that no compressed air excursions be made to 300 fsw when saturated at a storage depth of 60 feet with air as the breathing mixture.

Due to symptoms of bends during decompression from the 300 fsw excursion, it was recommended as a precaution that excursion times to 250 fsw be reduced from 60 to 45 minutes bottom time under open-sea conditions.

The lack of symptoms of oxygen toxicity and inert gas narcosis in studies, where the subjects breathed a normoxic mixture at storage depth and used air only on excursions, suggests that while working air excursions beyond 250 fsw should not be made from air saturation, they perhaps could be carried out from a normoxic saturation. The latter has two advantages. The first is in possibly allowing divers to "adapt" to a higher nitrogen partial pressure, thus reducing the narcotic impact of deeper air excursions. The other, rather obvious, advantage is the reduction of oxygen partial pressure in the storage breathing gas.

It is recommended at the present time, therefore, that air saturation be limited to depths of 60 feet and that air excursions from 60-foot air saturations be limited to 200 fsw for periods up to one hour. In special circumstances, however, with thorough training of divers and extra care being given to safety procedures, it should be possible to extend the excursion depth to 250 feet for periods of one hour. While it is recognized that the 250-foot excursion depth was used in the SCORE program, it is essential to provide a safety margin of sufficient magnitude to allow for those individuals who are especially sensitive to nitrogen narcosis and oxygen toxicity. Further data are needed before recommendations can be made regarding repetitive dives made under these conditions.

V. FIELD STUDIES

Many open sea programs have been and are continuing to be carried out in which extensive vertical excursions are made. The programs contained in this section are those which had as a primary objective, the test and

evaluation of advanced excursion diving procedures which had previously been studied in the laboratory. In each project described, every effort was made to conduct the dives with maximum safety and to document the results as accurately as possible under open-sea conditions.

V-A LORA

Introduction:

In 1973 a shallow water habitat program was carried out by members of the Memorial University of Newfoundland.

Location:	St. Phillips, Newfoundland
Date:	August 22-23, 1973
Duration:	24 hours, 16 minutes
Saturation Depth:	26 fsw
Breathing Gas:	Habitat - air Excursions - air
Aquanauts:	Two
Water Temperature:	54.5°F
Habitat Temperature:	70-78°F
Facility:	LORA Habitat - an 8 x 16 foot structure

Purpose:

To evaluate the habitat facility under operational conditions, to conduct routine hull maintenance; to observe fish behavior during a 24-hour cycle, and to test a new decompression procedure.

Excursions:

Four excursions were made by the two divers to a depth of 35 fsw. Three excursions were for 60 minutes and one was for 75 minutes. No difficulties were encountered on any excursions.

Decompression:

Upon completion of the fourth excursion, the two aquanauts spent 8 hours in the habitat at the storage depth of 26 fsw after which they proceeded directly to the surface with no decompression stops. No symptoms of bends were noted by either diver.

Summary:

The investigators concluded that "the divers did not reach full saturation at hatch depth," but that "the length of the dive was such that this was approached." The 8-hour "soak" period at the 26 fsw storage depth following the fourth excursion, was required to allow the nitrogen taken up during the excursions to be released and the tissues to reach equilibrium with that depth. The authors further concluded that, "It is possible to surface directly when fully saturated at the hatch depth (26 feet)" (English 1973).

During the period February 12-15, 1975 an additional saturation dive in Newfoundland was made using LORA. The saturation depth was again 26 fsw. The habitat was under the ice with a water temperature of 28.6° F. A total of 36 man-excursions to a depth of 35 fsw were made by the three aquanauts. The average excursion time was 38 minutes with the longest being 54 minutes. Upon completion of the mission, the aquanauts breathed oxygen for six 20-minute periods with 5-minute periods in between breathing habitat air. This was necessary to allow the divers to surface as quickly as possible following the last excursion. Following this procedure, the aquanauts entered the water and swam directly to the surface. Eighteen hours later the aquanauts flew from Newfoundland to Montreal. No symptoms of decompression sickness were noted.

V-B Hydro-Lab

Introduction:

The Hydro-Lab Underwater Research Program was a long-range scientific and educational program centered around the Hydro-Lab, a manned habitat that operated at either ambient or surface pressure.

The program was operated under the auspices of the Perry Foundation, Inc., Riviera Beach, Florida. Although a few earlier dives were made, the principal program began in February 1971.

As of December 1975, the Hydro-Lab system saturated 319 diver-scientists in teams of 2-4, at the habitat hatch depth of 42 fsw. The average saturation time was six days for each team. An additional 24 divers were saturated at a depth of 60 fsw for 5-7 days, making a total of 343 saturated diver-scientists. The shortest mission was 24 hours and the longest was 13 days. There have been over 100 separate missions. Table 27 shows the dates and number of divers saturated since 1971.

Purpose:

The Hydro-Lab Program was devoted primarily to providing marine scientists with a facility and an opportunity to conduct extensive studies relating to marine biology, geology, ocean dumping and other aspects of marine resource development. The Program also included studies of chemistry, physics,

TABLE 27

Summary of Hydro-Lab saturation missions

Dates		Number of Divers Saturated
February 1971 - December 1971		24
January 1972 - December 1972		53
January 1973 - December 1973		99
January 1974 - December 1974		113
January 1975 - December 1975		54
	Total	343

physiology, as well as ocean technology. As new diving procedures were developed they were tested using Hydro-Lab and subsequently used on a routine basis to provide additional flexibility to divers conducting marine resource studies from Hydro-Lab and elsewhere.

Location:	1.2 miles (123°) off Bell Channel Light, Lucaya, Grand Bahama Island
Date:	February 1971-December 1975
Duration:	1-13 days saturation
Saturation Depth:	42, 60 fsw
Excursions to:	250 fsw
Breathing Gas:	storage - air excursions - air
Aquanauts:	2-4 per team
Visibility:	40-125 feet
Bottom Water Temperature:	24.0-29.5°C
Surface Currents:	0-0.5 knots
Sea State:	0-15 feet (short period)

Facility:

Hydro-Lab, shown in Fig. 5, normally rests at a depth of 47 feet, although the bottom hatch is at 42 feet. The area is surrounded by large coral heads. Coral channels continue a short distance seaward into 70-80 feet

Photo: Dick Clarke

Fig. 5. Hydro-lab habitat.

of water. A drop-off or wall beginning at a depth of 150 feet is approximately 1,200 feet from the habitat. Figure 6 depicts the bottom topography surrounding Hydro-Lab. Hydro-Lab is an 8 x 16 foot cylindrical chamber with an attached 3 x 10 foot submarine dry transfer tunnel. It contains two bunks, air conditioner, dehumidifier, electrical panel for 110 AC and 12 volts DC, communications radio, sound power phones, CO_2 scrubber, air inlet valves, and emergency and oxygen breathing masks. It also has a diver lockout trunk, portable toilet, interior 110 and 12 volt lights,

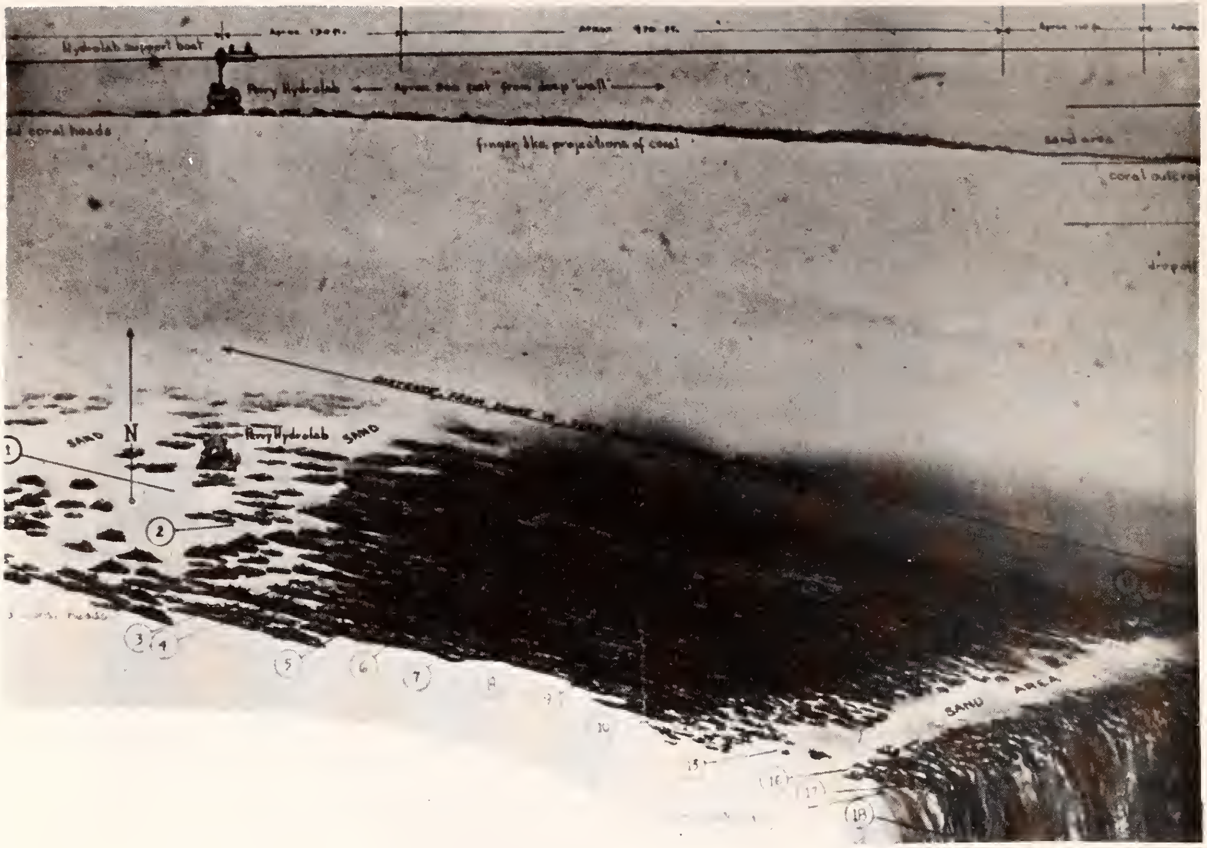

Fig. 6. Bottom topography of Hydro-lab site.

exterior 1000 watt light, seven windows (one of which is four feet in diameter), 12-volt emergency batteries, tables, fresh water shower and hatch attachments.

The habitat can support 3-4 scientists for periods up to 14 days. The life support system maintaining the habitat from the surface is built into a 23-foot fiberglass boat hull. This contains a 24 h.p. Lister diesel generator (7.5kw AC), a high pressure (3000 psi) air compressor, a low pressure (200 psi) air compressor, 250-gallon fuel and water tanks and a 12V DC system.

The total system is completely self-sufficient, eliminating the need for a manned support vessel overhead. The system maintains internal breathing air, high pressure air to fill scuba tanks, supplies fresh water and generates electrical power to the habitat. Life support is designed to operate more than seven days with only minimum on-site maintenance. An emergency system within the habitat can support four persons for several days.

A trunk with intermediate hatches allows diver lockouts should the habitat be at atmospheric pressure. The lockout trunk can be operated by either a diver located within the trunk or by someone within the habitat. Decompression takes place and is controlled from within the habitat itself.

A captured-air stand-up booth large enough for four men was used outside the habitat as a safety and bottom air-filling station. A four-man decompression chamber with a 225 fsw capability is located on shore at the International Underwater Explorers Club. Divers can normally be transported from the habitat to this chamber in 10 minutes. Scientific laboratory space was also available at the shore facility.

Divers:

The age range of Hydro-Lab aquanauts was from 18 to 56 with an average age of about 30. Of the 343 aquanauts about 11% were females having an average age of 27.5 years. Aquanauts were selected based on the merits of scientific proposals submitted, physical condition, and diving experience. Each aquanaut was required to have a current physical examination. In addition, a pre- and post-dive examination was administered at the Hydro-Lab site. Aquanauts also submitted a resume of diving experience and certification. Divers saturating for the first time received an on-site diving check-out prior to their mission. Certification alone was not considered to be sufficient for a diver's acceptance, although lack of it was not necessarily grounds for rejection. Some divers had limited diving experience, but were allowed to saturate due to the nature of their work and their ability to conduct it safely.

Limitations on excursion-diving from Hydro-Lab, although based partially on previous experience and certification, were based mainly on performance during the open sea check-out dive. Divers who performed poorly were either rejected entirely from saturation diving or were limited to short excursions. The Hydro-Lab program had two full-time operational personnel: the project manager and assistant manager. Each team was required to bring at least two additional support divers.

Procedures:

Prior to the availability of the NOAA OPS vertical excursion profiles in 1973, excursions from Hydro-Lab beyond a depth of 90 fsw were not permitted. This was a safe practice since the present excursion profiles allow a 5-hour excursion to 90 fsw from a 40-fsw saturation and unlimited time from a 60-fsw saturation.

The following procedures were used for all deep excursions from Hydro-Lab:

Pre-Excursion

1. The dive plan discussed with and approved by the Hydro-Lab management.

2. A transect line placed from Hydro-Lab to the maximum depth of the excursion.

3. Buoys placed along the transect line from the Hydro-Lab to the edge of the submerged wall at a depth as near as possible to the saturation depth so the aquanaut maintains the saturation depth until reaching the wall.

4. Prior to each excursion beyond 600 feet swimming distance from Hydro-Lab, the divers contacted Hydro-Lab base by radio, reviewed the excursion plan, and received approval.

Excursion Rules

1. The excursion was cancelled if conditions were, in the opinion of the Hydro-Lab management, too rough, water visibility poor, currents too strong, or otherwise unsafe. Only under special, pre-planned circumstances were excursions made to depths greater than 200 fsw.

2. Each diver departed Hydro-Lab, using a full set of double 72 foot^3 scuba tanks, with an "octopus" regulator, or equivalent. If necessary, the divers were accompanied by a surface support boat. All excursions below a depth of 130 fsw required a surface support boat. A surface support diver was in the water to monitor the saturated divers if deemed necessary by the Hydro-Lab management. Spare scuba tanks were in the surface support boat or on the bottom to serve as emergency air supply or for extended excursions.

3. Aquanauts were required to maintain visual contact with the transect buoys or the transect line at all times during excursions.

4. Aquanauts proceeded at the pace of the slowest swimmer along the transect line, maintaining the saturation depth.

5. Bottom time for the excursion began when the aquanauts went below saturation depth.

6. Aquanauts swam slowly down the buoy line and changed to an unused set of double tanks if necessary. If the used set of tanks did not contain at least 1000 psi, the excursion was aborted.

7. Excursion times normally were conducted in accordance with NOAA OPS no-decompression tables. Decompression excursions required separate tables and special equipment.

8. When extra tanks were on the bottom at the conclusion of an excursion, or when the tank pressure reached 600 psi for any aquanaut, all aquanauts returned to the extra set of doubles. They changed to these if the set used on the excursion had less than 1000 psi. If the excursion was made without extra tanks on the bottom, all aquanauts returned to the saturation depth when the tank pressure reached 1000 psi for any one aquanaut.

9. The aquanauts ascended at 30 feet per minute up the buoy line, and returned to Hydro-Lab at the pace of the slowest swimmer, maintaining the saturation depth, except in the case of a decompression excursion where they held at each decompression stop during the swim back.

10. Bottom time for the no-decompression excursions ended when the aquanauts returned to the saturation depth. For decompression excursions, bottom time ended at the moment of ascent.

Decompression:

The aquanauts decompressed inside the habitat. Prior to commencing the mission, the Hydro-Lab management instructed the team on decompression procedures which were carried out by the aquanauts themselves upon completion of the mission. The decompression schedule used for 42-foot saturation missions is shown in Table 28.

Following decompression, a surface support diver swam to the habitat to assist the aquanauts in locking out and ascending to the surface. Aquanauts remained near the shore-based recompression chamber for 24 hours and did not fly for 36 hours after completing decompression. One three-man, 60-foot saturation mission was carried out in which decompression was accomplished in accordance with the schedule shown in Table 29. Other decompressions were successfully carried out using Table 24 including several from a saturation depth of 42 fsw.

In using Table 29, the saturation depth is selected from the left hand column; the first stop, gas mixture and time from the middle column; and all subsequent stops from the right hand column. For example, for an 80-foot normoxic saturation, the first stop is 60 fsw on air for three hours. The next stop is at 55 fsw on air for five hours, etc.

Results:

A total of 100 no-decompression and four decompression excursion dives were made from a 42-foot saturation depth to depths greater than 125 feet and to 200 feet respectively.

In October 1973, a series of 16 no-decompression excursions from 42 fsw saturation were made by two aquanauts to depths ranging from 50-200 fsw. Fig. 7 summarizes the depths and times. No symptoms of bends were noted during any of these excursions. Fig. 8 illustrates the excursion profile used by 25 different aquanauts in making excursions to a depth of 130 fsw in July and August 1974. These excursions required each aquanaut to swim approximately 3,000 feet and involved a 33-minute bottom time. No symptoms of bends occurred during any of these excursions. The maximum bottom time for a 130-foot, no-decompression excursion is 70 minutes, so the lack of bends is not surprising. Longer bottom times were not attempted because the divers were college students participating in an advanced scientific diving training program.

TABLE 28

Hydro-Lab decompression profile from an air saturation at 42 fsw

Depth (ft)	Rate of Ascent (ft per min)	Time (min)	Breathing gas
42 to 24	2	9	air
24 stop	-	180	air
24 to 20	1	4	air
20 stop	-	180	air
20 to 16	1	4	air
16 stop	-	180	air
16 to 12	1	4	air
12 stop	-	75	oxygen
12 to 8	1	4	air
8 stop	-	80	oxygen
8 to 4	1	4	air
4 stop	-	90	oxygen
4 to surface	1	4	air

Decompression Time----9 hours 33 min. air
4 hours 5 min. oxygen
Total 13 hours 38 min.

Also in July 1974, a series of excursions was made by three aquanauts to depths of 150 fsw and 200 fsw from a 42-foot saturation depth. Fig. 9 is typical of the 150-foot excursions and represents a total of 12 excursions made by two females and one male aquanaut. Bottom times at 150 fsw were between 21 and 42 minutes for ten of the excursions. The other two excursions were "bounce" dives to 150 feet as part of a longer excursion at a shallower depth. As in each Hydro-Lab excursion, a swim of about 3,000 feet was required. Seven 200-foot excursions made by the same three aquanauts are shown in Fig. 10. In all of these excursions, the primary mission was to collect biological specimens and to photograph the deep reef wall. The

TABLE 29

Decompression schedules following normoxic/air saturation exposure*

	First Stop			Subsequent Stages		
Saturation Depth Range (fsw)	Depth (fsw)	Gas	Time At Stop (hr:min)	Depth (fsw)	Gas	Time At Stop (hr:min)
96-100	80	Air	3:00	75	Air	4:00
91-95	75	Air	3:00	70	Air	4:00
86-90	70	Air	3:00	65	Air	4:30
81-85	65	Air	3:00	60	Air	4:30
76-80	60	Air	3:00	55	Air	5:00
71-75	55	Air	3:30	50	Air	5:00
66-70	50	Air	3:30	45	Air	5:00
61-65	45	Air	3:30	40	Air	5:00
56-60	40	Air	4:00	35	Air	0:30
				35	Oxygen	1:00
51-55	35	Oxygen	1:00	35	Air	0:30
				35	Oxygen	1:00
				30	Air	2:00
46-50	30	Air	2:00	30	Oxygen	1:00
				25	Air	0:30
				25	Oxygen	1:00
41-45	25	Oxygen	0:30	25	Air	0:30
				25	Oxygen	1:00
				20	Air	3:00
36-40	20	Air	1:30	20	Oxygen	1:00
				15	Air	0:30
				15	Oxygen	1:00
31-35	15	Oxygen	1:00	15	Air	0:30
				15	Oxygen	1:00
				10	Air	4:00
26-30	10	Air	2:00	10	Oxygen	1:00
				5	Air	0:30
				5	Oxygen	1:00
				5	Air	0:30
22-25	5	Oxygen	0:30	5	Oxygen	1:00
				30**	Oxygen	0:30
0-21	No Decompression			Surface		

*This table was calculated based on a normoxic storage breathing gas. Because the Hydro-Lab atmosphere was air, the decompression began at the 46-50 fsw level (the air equivalent depth) following a saturation at 60 fsw.

**Not used during Hydro-Lab program

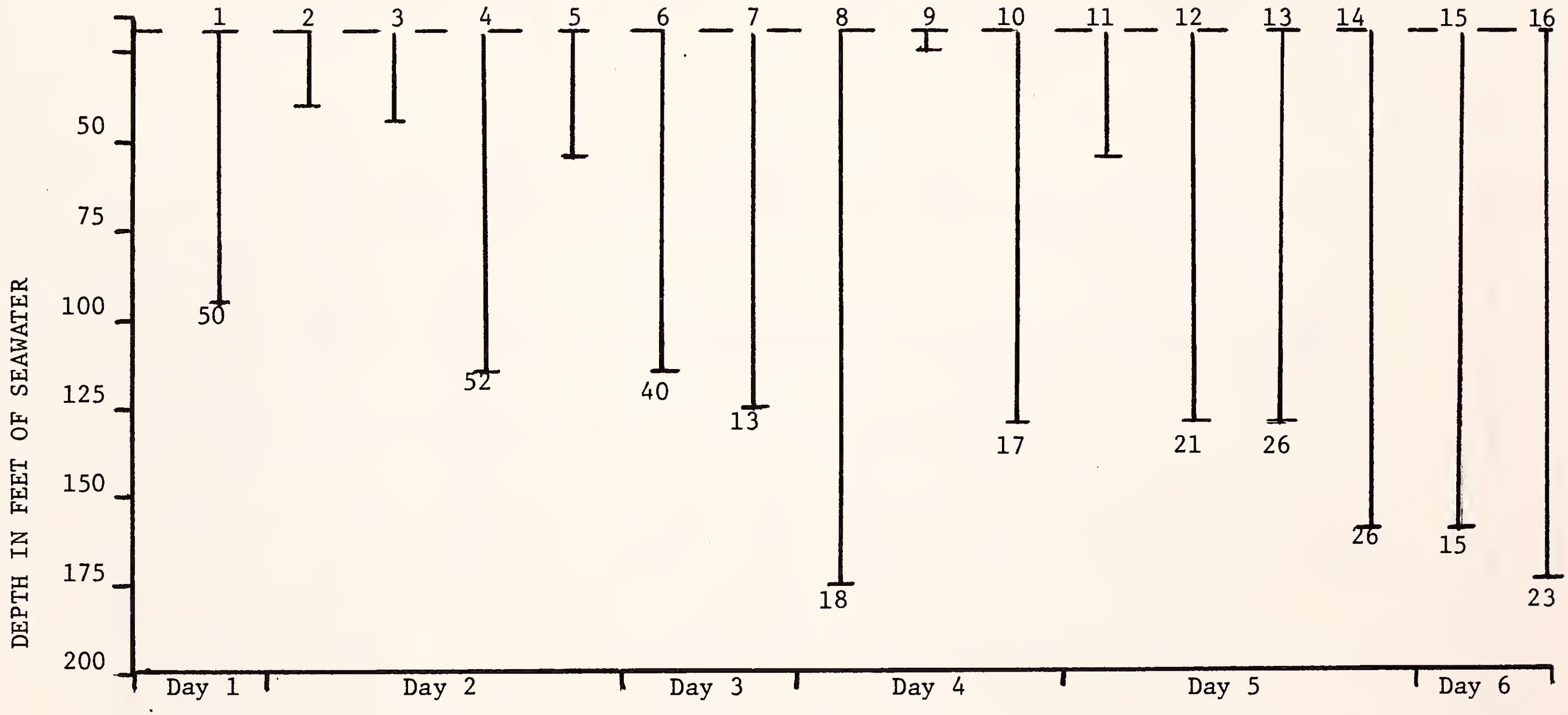

Fig. 7. Summary of 16 no-decompression excursions made by two aquanauts from air saturation at 42 fsw,

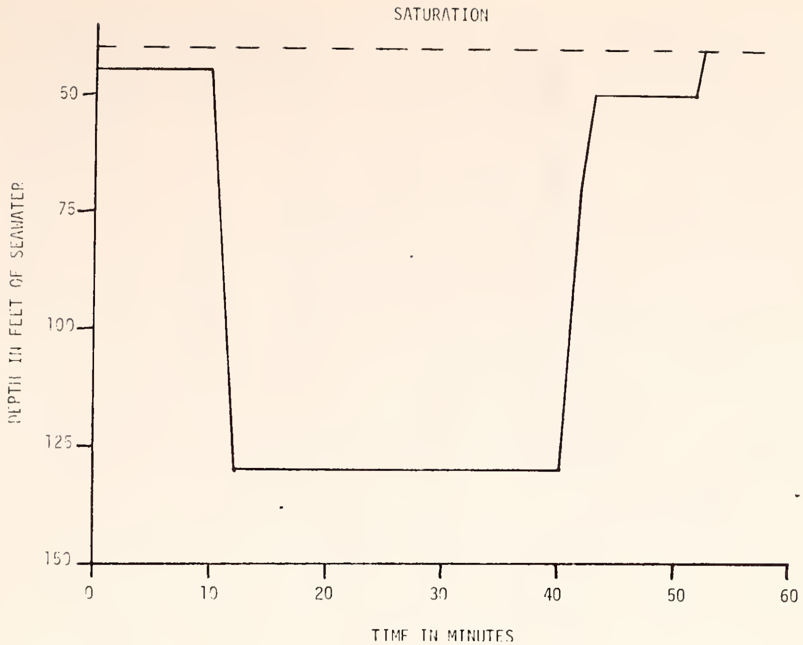

Fig. 8. No-decompression profile used by 25 aquanauts for excursions to 130 fsw from air saturation at 42 fsw.

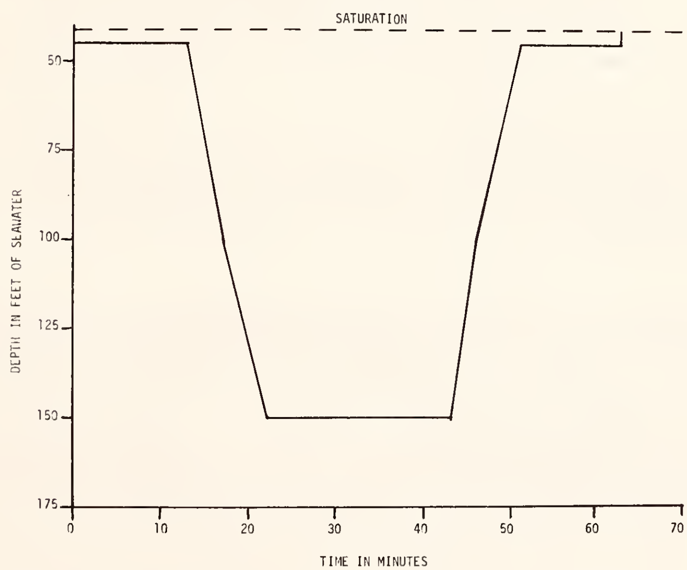

Fig. 9. Typical no-decompression profile used by three aquanauts for 12 excursions to 150 fsw from air saturation at 42 fsw.

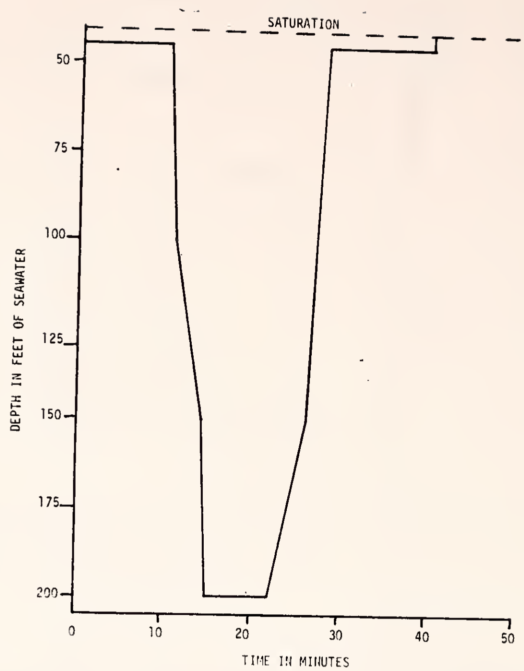

Fig. 10. Typical no-decompression profile used by three aquanauts for seven excursions to 200 fsw from air saturation at 42 fsw.

bottom time for these excursions was 18 or 19 minutes with no symptoms of bends occurring.

During a different mission in August 1974, a series of 13 excursions was conducted without incident to depths of 165-175 fsw by four divers to carry out geological and oceanographic studies. These excursion profiles are shown in Fig. 11.

In December 1974, a series of no-decompression excursions was made to depths ranging from 180-200 fsw by the two operations directors of the Hydro-Lab program (Figs. 12 and 13). They all were made from a 42-foot air saturation and were carried out without incident. It may be noted that some of the excursions depicted in Figs. 12 and 13 have longer bottom times than those allowed by the NOAA OPS tables. This is because during these initial excursions the bottom time ended once the aquanaut left the maximum depth attained rather than when the storage depth was reached.

The two, two-man excursions made to a depth of 200 and 80 feet for periods of nine and 28 minutes respectively are shown in Fig. 14. The final no-decompression excursion was made to 165 feet for 31 minutes and is shown in Fig. 15. No symptoms of bends were noted during or following any of these excursions.

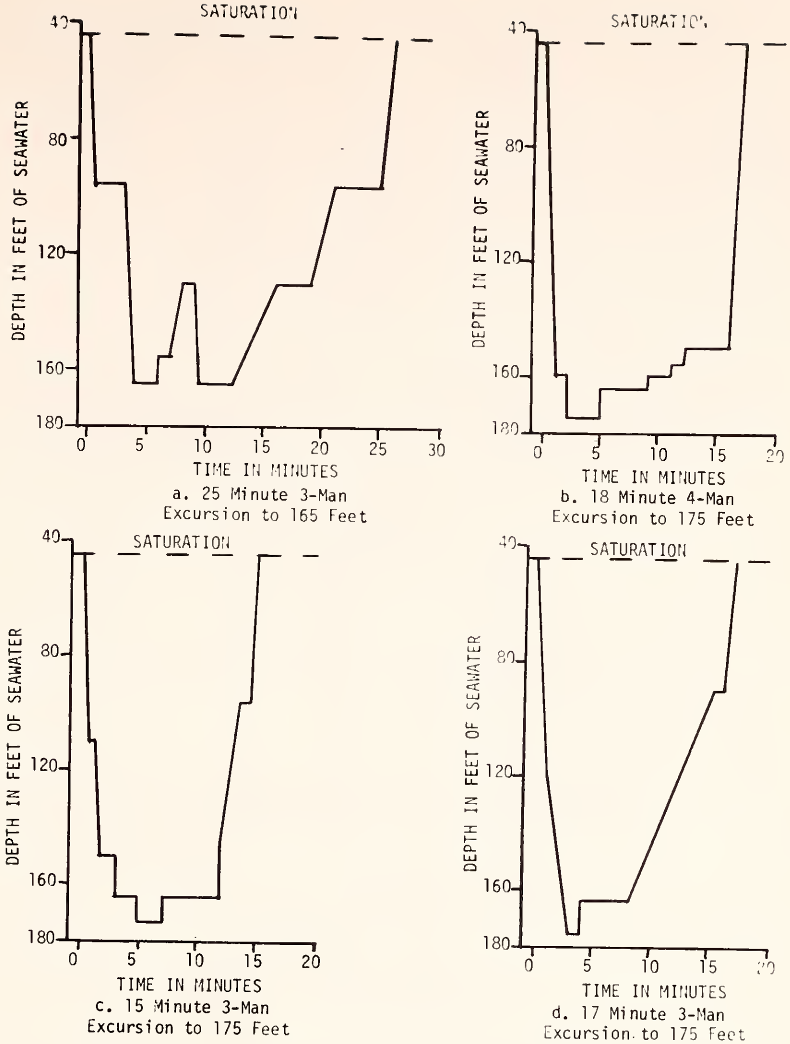

Fig. 11. No-decompression profiles for 13 excursions to depths of 165-175 fsw from air saturation at 42 fsw.

During this same December 1974 mission, two, two-man decompression excursions were made to a depth of 200 feet as shown in Fig. 16. The purpose was to demonstrate the feasibility of conducting decompression excursions from Hydro-Lab prior to the SCORE project. The decompression times computed by Tarrytown Labs (Table 30) were actually doubled during these excursions to ensure a satisfactory safety margin.

Biomedical Program:

During several Hydro-Lab missions, an integrated, self-contained Doppler bubble detector with monitoring and recording equipment was provided for

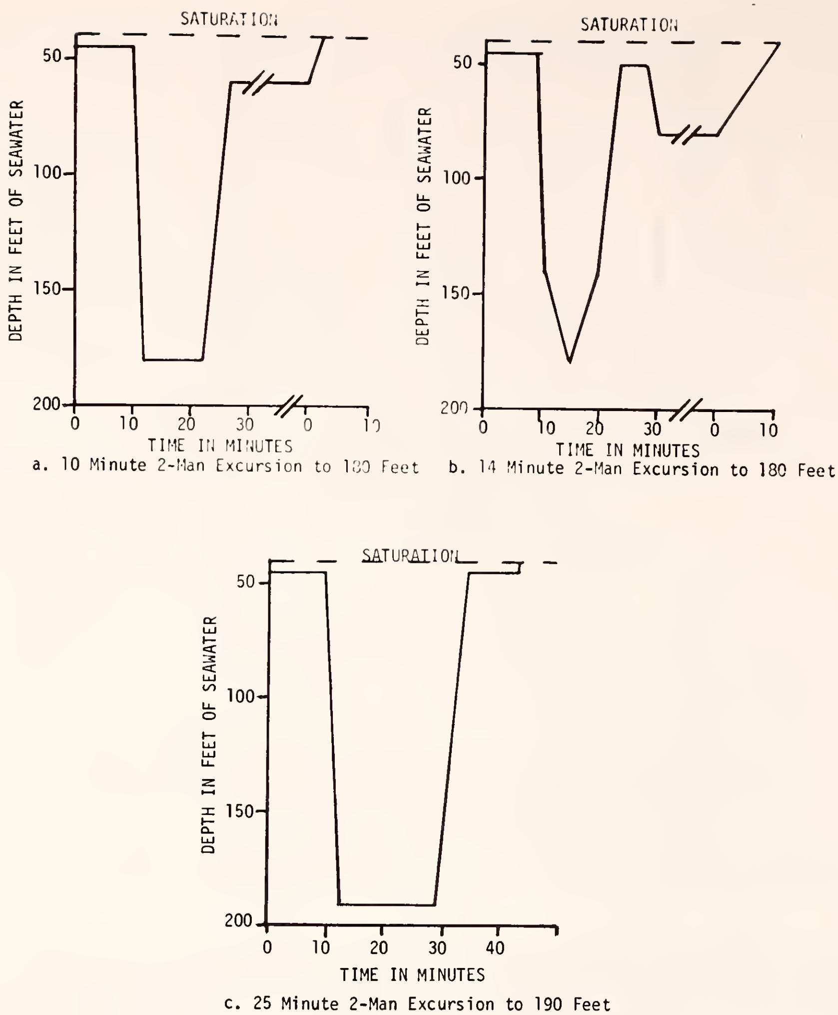

Fig. 12. No-decompression profiles for six excursions to depths of 180-190 fsw from air saturation at 42 fsw.

use by the Applied Physics Laboratory of the University of Washington. The aquanauts were trained to make recordings after each excursion and during decompression. In this manner, data from a large population of divers were collected and the use of equipment in the field was demonstrated. Even though there were some technical problems, good recordings were obtained from several teams of divers. In no instance either after excursions, including those to 200 feet, or during decompression, were bubbles detected. While this does not preclude the existence of bubbles, it does indicate that the decompression tables and the excursion profiles probably were on the conservative side.

Other biomedical studies included measures of vital capacity, metabolic rate, cardiovascular function, brain wave activity, stress, fluid volume

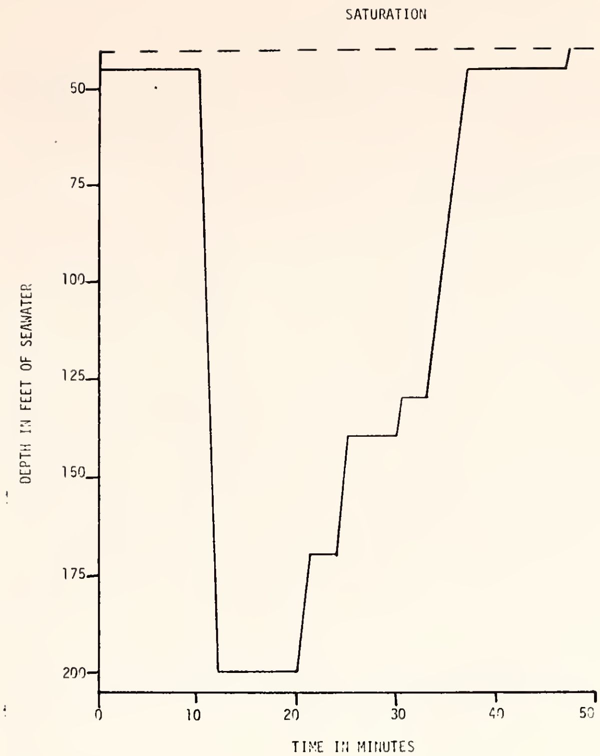

Fig. 13. Twenty-seven minute two-man excursion to 200 fsw from air saturation at 42 fsw.

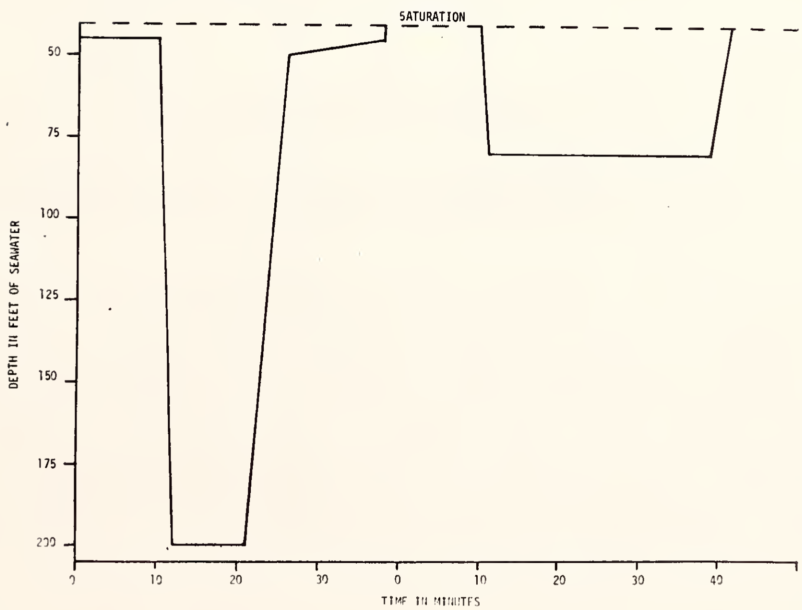

Fig. 14. Two-man exursions to 200 fsw and 80 fsw from air saturation at 42 fsw.

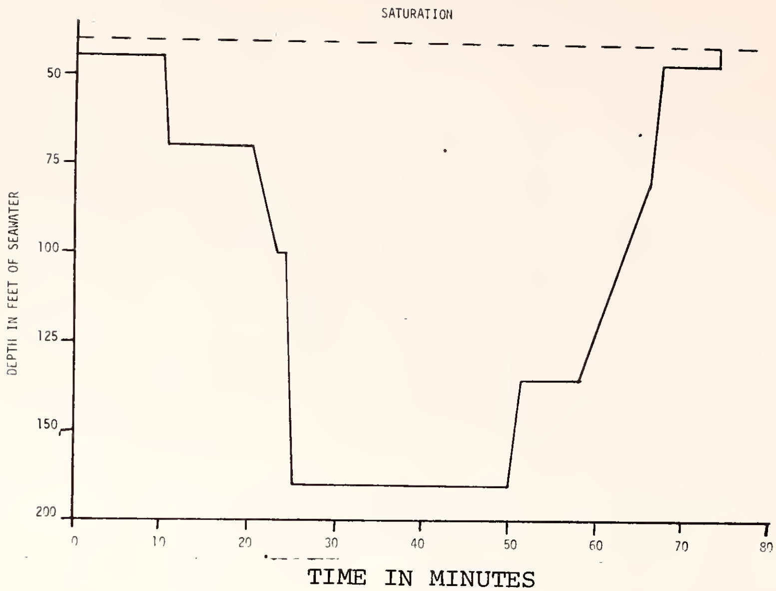

Fig. 15. Two-man excursion to 165 fsw from air saturation at 42 fsw.

regulation, and blood chemistry. Because none of these studies were directly correlated with excursion dives, they will not be discussed here. It will suffice to say that the results were all negative with the exception of blood chemistry.

Hematology and Blood Chemistry

Two studies were conducted during the Hydro-Lab program. In the first study (April 1973), 20 young-adult divers, 19 male and 1 female, served as the experimental subjects. Each subject was saturated for three days at a depth of 42 fsw. Descending excursions did not exceed a depth of 130 fsw. Decompression was carried out according to the schedule shown in Table 28. The divers were university graduate students completing the "Scientist-in-the-Sea" training program, and their instructors. Twenty-five ml blood samples were collected from a forearm vein, occluded with a wide tourniquet, into disposable plastic syringes using disposable 20-gauge needles. The blood was immediately distributed into test tubes containing the appropriate anticoagulant for a particular test. Samples were collected the day before the dive, 30 min before the dive, 30 min after decompression, and daily for three days thereafter where possible. Although it was not possible to maintain strict fasting conditions at the time of sampling, an effort was made to collect samples just before a meal, so that alimentary lipemia was minimal.

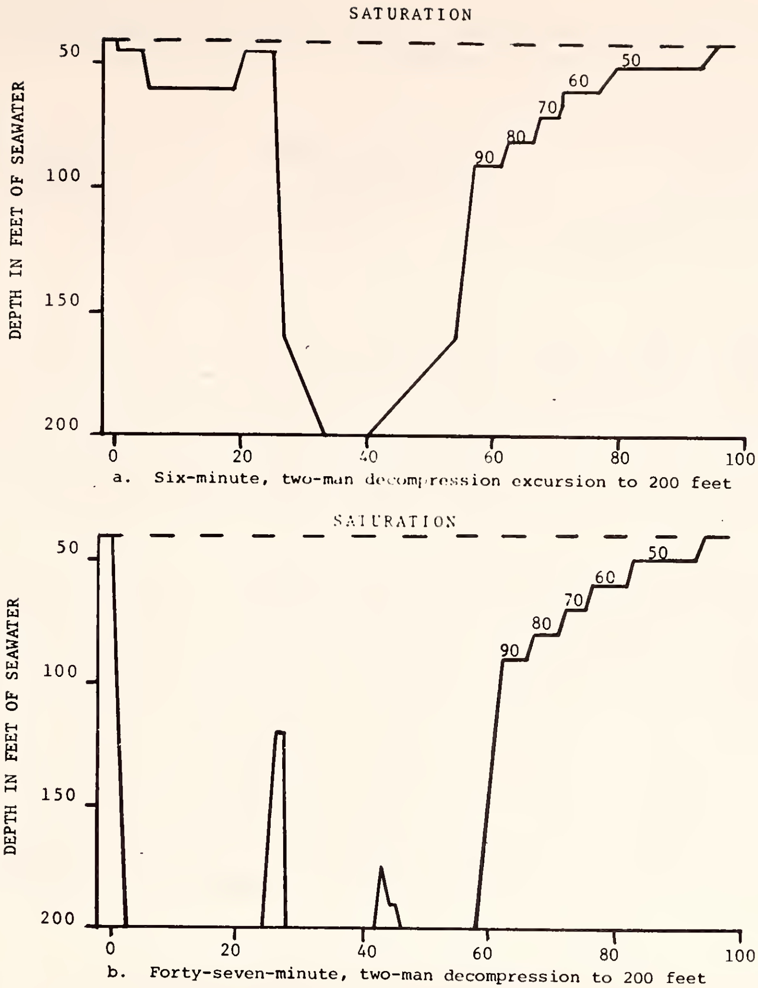

Fig. 16. Decompression excursion profiles for four excursions to 200 fsw from air saturation at 42 fsw.

In the second study (August 1973), twelve healthy, young-adult males, all members of the University of Western Ontario diving Club, served as volunteers. The depth, decompression profile, and swimming excursions were the same as in the first study except that the dive extended over five days, including decompression time. Blood was collected, from each diver 48 hours, 24 hours, and immediately pre-dive; once during the dive (dive day 2 or 3); and immediately, 24 hours, 48 hours, and 72 hours post-dive. Each in-dive blood sample was vented with a 20-gauge needle and decompressed in the transport pot from 2.4 ATA. Decompression took at least 10 minutes. Sample volume was kept to the necessary minimum (20-25 ml) and blood was always collected before a meal to minimize alimentary lipemia.

TABLE 30

Decompression schedule for excursions to 200 fsw from air saturation at 42 fsw*

Depth (ft)	Rate of Ascent (ft per min)	Time (min)
200 to 90	30	4
90 Stop	--	5
90 to 80	10	1
80 Stop	--	4
80 to 70	10	1
70 Stop	--	3
70 to 60	10	1
60 Stop	--	6
60 to 50	10	1
50 Stop	--	16
50 to 42	10	1
	Total	43 Minutes

* The lock-out submersible Johnson-Sea-Link was standing by as a back-up system during these excursions.

Drug Administration

Two members of each saturation team of four divers were assigned randomly to a treatment group or a placebo group. The treatment group received 300 mg three times daily of VK744CL2 (chemical name: 2-[(2-aminoethyl)amino] 4-morpholino-thieno [3,2-d] pyrimidine dihydrochloride) for 24 hours before the dive, during the dive, and for three days thereafter. The placebo group received capsules identical in appearance and number but containing lactose. Drug administration was timed so that two blood samples were collected prior to medication and one, i.e., the pre-dive sample, after the subjects had taken four doses (1200 mg). Double-blind procedure was followed throughout and each diver was coded separately so that in the event of a possible drug reaction, his medication could be identified without compromising the entire project. This never occurred. A member of the Hydro-Lab staff held the drug code.

When the results of the hematology and blood chemistry program were analyzed, it was found that, with one exception, all of the subjects in both saturation-dive groups demonstrated a drop in circulating platelet count after surfacing. The extent of the drop ranged from 11.6 - 55.6% with most subjects showing the lowest count 24-48 hours after surfacing. Because all subjects did not show maximum decrease on the same day, the mean maximum drop for the six subjects was calculated (34.5% ± 7.25 SEM ($p < 0.001$). The daily mean-percentage decreases were statistically significant in the 24-hour ($p < 0.01$) and 48-hour samples ($p < 0.05$). The seventh subject was not included in the calculations because he was thrombocytopenic prior to the saturation.

It was concluded that saturation exposure of up to seven days in Hydro-Lab does not elicit significant tissue damage, as indicated by the normal isoenzyme pattern following decompression. Loss of platelets however, does occur and although not of sufficient magnitude to warrant concern, suggests that microbubble formation may occur during very safe decompressions. Complete details of these studies may be found in Philp, Freeman, Francey and Bishop (1975).

It should be noted that the decrease in circulating platelets during the Hydro-Lab studies was not found in the NOAA OPS program. This difference in findings may be due to the fact that in Hydro-Lab the aquanauts made a rapid ascent to a depth of 24 fsw and then stopped every four feet for the remainder of the decompression. In NOAA OPS, on the other hand, the decompression was continuous throughout, which may have prevented small bubbles from forming and serving as a nucleus for the agglutination of platelets. Much additional work is required in order to identify the physiological or pathological significance of post-decompression thrombocytopenia and to determine the effects of repetitive diving, saturation diving, abnormal platelet function and drug-induced alterations in platelet activity.

<u>Summary</u>:

The Hydro-Lab program has provided a facility for a significant number of excursion dives. There were no cases of bends following any excursion and no hard evidence of bends following decompression. A total of four out of 343 saturated aquanauts were recompressed as a precautionary measure following symptoms that would make the administration of hyperbaric oxygen desirable.

V-C <u>PRUNE I</u> (<u>P</u>uerto <u>R</u>ico <u>U</u>ndersea <u>N</u>itrogen <u>E</u>xcursion)

<u>Introduction</u>:

PRUNE I was the sixth in a series of 10 missions designed to assess the marine resources along the Southeast Coast of Puerto Rico. Although the PRUNE program took place in about 100 fsw, all of the other nine missions took place at depths of 50 to 60 feet and were exclusively marine scientific

efforts. Over 50 marine scientists and engineers were saturated during these 10 missions. The work was carried out under the auspices of the Marine Resources Development Foundation with support from the Puerto Rican Government and NOAA.

Purpose:

PRUNE I involved marine biological surveys, underwater color visibility experiments, a biotelemetry study, a cosmic ray physics program, and the field evaluation of ascending excursion profiles. Topographical constraints did not permit the testing of descending excursion profiles as the maximum depth within a safe swimming distance of the habitat was 130 feet.

Location:	Ten miles off the Southeast Coast of Puerto Rico
Date:	April 24 - May 4, 1973
Duration:	14 days
Saturation Depth:	95 fsw
Breathing Gas:	Habitat - 90-96% Nitrogen, 4-10% Oxygen Excursions - Air
Aquanauts:	Four
Water Temperature:	74°F
Habitat Temperature:	80°F
Habitat Humidity:	50-60%
Facility:	La Chalupa Habitat

La Chalupa has a 48' x 20' x 10'8" barge-like exterior structure containing two steel chambers, each 8' diameter x 19' long (Fig. 17). One chamber is a living compartment with two 41" windows, four water beds, a desk, storage space, a small freezer, and a sink. The living compartment is capable of withstanding 50 psi internal pressure and is used as a decompression chamber when the habitat is surfaced at the end of a mission. The other chamber is capable of withstanding 50 psi external pressure and is the control compartment. It has one 41" diameter window, a decompression control station, a galley, electrical controls, TV monitors, and other equipment. In an emergency, this compartment can be used as a decompression chamber on the sea floor to a depth of 100 fsw.

Both compartments have a transfer lock attached to an upper hatch, permitting transfer of personnel and equipment to a capsule located on the deck of the barge when the chamber is at pressure other than ambient. These capsules may also be used to evacuate personnel to the surface under pressure

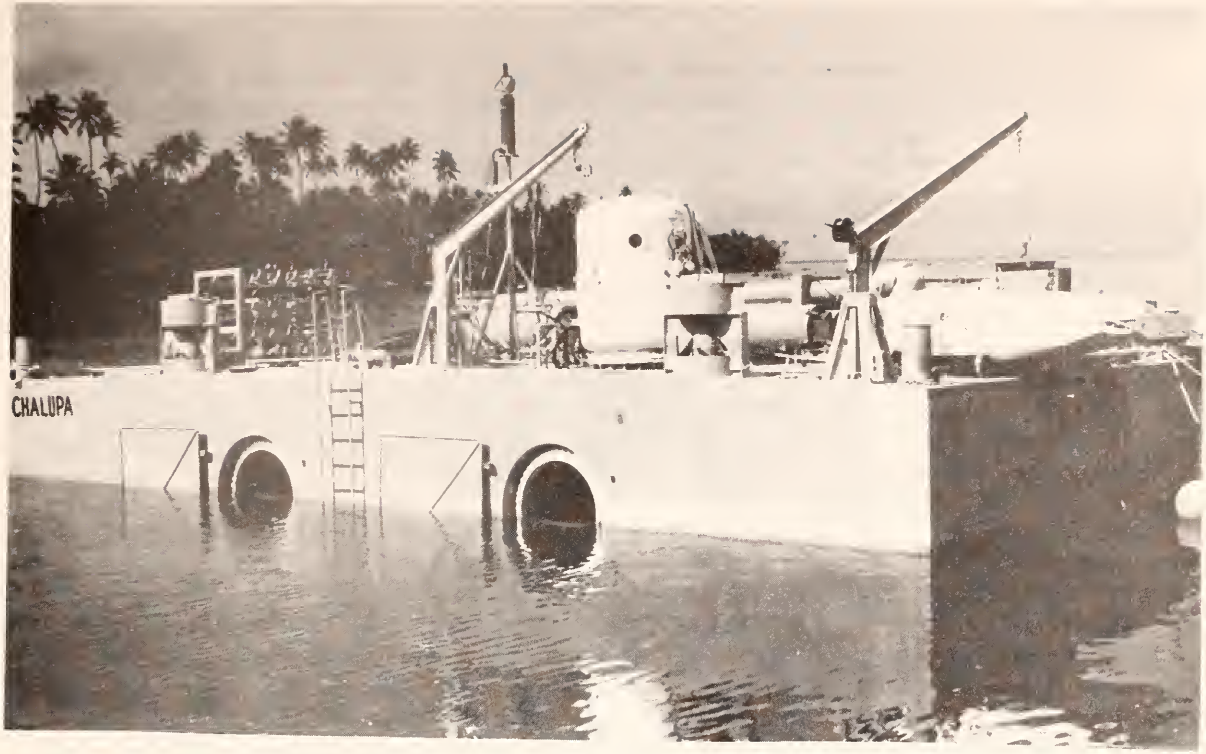

Fig. 17. La Chalupa habitat.

in the event of an emergency. An unmanned life support buoy, located on the surface, provides the habitat with power, high and low pressure air, and fresh water.

The sub port, or wet lab, a captured air-space located between the living and control chambers and open at the bottom, is used for entrance into the habitat, dry access between living and control compartments, storage space for scuba gear, a shower, a toilet, and 35 $feet^2$ of work space on stainless steel tables.

In case of loss or removal of the life support buoy, the habitat is equipped with emergency batteries capable of operating CO_2 scrubbers and emergency lights for 48 hours. Additional emergency facilities provide for seven days of air, food, and scrubbing capabilities. High pressure air cylinders on the habitat contain 5600 standard cubic feet (SCF) of compressed air which could be used to operate the habitat air system, and to surface and de-ballast the habitat in event of loss of air compressors or life support buoy.

Aquanauts:

The aquanauts were experienced male divers between the ages of 32 and 45. Each was required to undergo a physical examination including a complete series of long bone x-rays, and a physical conditioning program. Two had been saturated previously in open sea experiments.

Procedure:

Once each day an ascending excursion was made by two or three divers. The divers followed the habitat umbilical to the prescribed depth and maintained physical contact with it for the entire excursion. Wrist depth gauges were used which were calibrated daily with the master gauge in the habitat. The ascent rate was approximately 30 feet per minute. All excursions were made breathing air from either a standard set of double scuba cylinders or a hookah (breathing hose) attached to the habitat.

The excursion times were calculated during the NOAA OPS program, especially for use during PRUNE I. The times permit longer excursions than those tested during NOAA OPS, partially because only one excursion was made each day (see Tables 10 and 11, Section IV-A). Further, the seafloor topography did not permit preceeding downward excursions of any consequence. Thus, the calculation of tissue loadings was less complicated. The excursion times also were longer than the published tables because an additional margin of safety was introduced for general use in the NOAA Diving Manual (1975).

The divers constantly checked the time during each excursion and questioned one another for any symptoms of bends. On long excursions the time was passed observing local reef inhabitants. Excursions were made on 10 successive days at times selected to be compatible with other planned activities. Visibility and current conditions varied. The maximum current experienced during an excursion was 0.8 knots.

Results:

Twenty-three man-excursions were successfully completed. Two excursions each were made to depths of 25, 30, 40, 50, and 60 fsw. Table 31 gives a brief summary of these excursions and their results. In general, no real bends were noticed, although a few niggles were observed by one diver during some excursions. These symptoms are noted in the table.

Decompression:

Upon completion of the 14-day mission, an uneventful 49-hour and 20-minute-decompression was completed (Table 32) using the schedule calculated for Tektite II (Miller, Vanderwalker, and Waller, 1971).

Summary:

The absence of significant problems during either the NOAA OPS studies or PRUNE I, suggests that the ascending excursion tables developed and published

TABLE 31

Results of ascending excursions from a saturation depth of 95 fsw

Excur. Depth	Duration	Habitat Mix, N/O_2	Equipment	No. of Divers	Symptoms
(ft)	(min)				
60	55	96/4	Hookah	2	None.
60	55	95/5	.... do	2	Niggle, right knee.[1]
50	30	90/10	.... do	2	Niggle, left elbow.
50	31	95/5	Scuba	3	None.
40	18	94/6	.... do	2	Slight niggle, right knee.
40	18	96/4	.... do	2	None.
30	7	94/6	.... do	2	Do.
30	7	95/5	.... do	3	Niggle, right knee.
25	2	95/5	.... do	3	Niggle, left elbow.
25	2	93/7	.... do	2	None.

[1] Same diver each time.

are safe for use under the conditions prescribed. As more information on vertical excursion profiles becomes available, it will facilitate selection of the most effective depths at which to place ocean floor laboratories. Also, the upward excursion data will add to the margin of diving safety by demonstrating the depth limits to which saturated divers can ascend briefly should they become lost or injured.

V-D PRUNE II (Puerto Rico Undersea Nitrogen Excursion)

Introduction:

PRUNE II, conducted one year after PRUNE I, was the tenth in the series of eleven missions described in PRUNE I. Three of the same divers took part in both PRUNE I and II. As with PRUNE I, the aquanauts were required to undergo a physical examination prior to and following the mission.

TABLE 32

Decompression schedule used for PRUNE I and II**

Depth (fsw)	Time at Stop (min)*	Breathing Mixture
103 - 90	10	Air
90	60	Air
85	90	Air
80	100	Air
75	110	Air
70	120	Air
65	360	Air
60	140	Air
55	160	Air
50	160	Air
45	10	Oxygen
45	150	Air
40	130	Air
35	20	Oxygen
35	150	Air
30	360	Air
25	30	Oxygen
25	150	Air
20	150	Air
15	50	Oxygen
15	120	Air
10	160	Air
5	60	Oxygen
5	110	Air

Total: 49 hr, 20 min; oxygen breathing, 2 hr, 50 min

* Ascent rate between stops, 1 ft per min. Last 5 min of each stop used to ascend to next stop

** Lambertsen (in Pauli and Cole, 1970)

Purpose:

This project was designed principally to test the NOAA OPS descending excursion profiles to a depth of 300 fsw, and to measure objectively any evidence of inert gas narcosis, using tests of time estimation and mental arithmetic. A secondary objective was to conduct a survey of benthic marine organisms.

Location:	Ten miles off the Southeast Coast of Puerto Rico
Date:	March 18-29, 1974
Duration:	11 days
Saturation Depth:	106 fsw
Breathing Gas:	Habitat - 90-96% Nitrogen, 4-10% Oxygen Excursions - Air
Aquanauts:	Four
Water Temperature:	74°F
Habitat Temperature:	80°F
Habitat Humidity:	50-60%
Facility:	La Chalupa Habitat (see PRUNE I for description)

Dive Site:

The habitat (Fig. 17) was located approximately 10 miles off the southeast coast of Puerto Rico at a depth of 110 feet (saturation depth 106 fsw).

The topography of the dive site was dominated by three major features: a broad terrace, an uninterrupted buttress reef on the outer edge of the terrace, and a relatively steep terraced dropoff on the outer side of the reef into deep water as shown in Fig. 18. The buttress reef (probably a submerged ancient reef) was continuous and without spur and groove features for at least one-half mile (probably 20-30 miles) on either side of the site. This ridge had a relief of 45 feet and was approximately 400 feet wide. Its location, seaward of the habitat, made it necessary for the divers to ascend from the saturation depth of 106 fsw to a depth of 65 feet on each excursion to reach deep water seaward of the buttress reef. The bottom on the outer edge of the Puerto Rican Shelf, seaward of the buttress reef, dropped away in a series of ill-defined terraces from a depth of approximately 100 feet on the outer side of the terrace to 130 feet. The slope was approximately 20 degrees. Beginning at about 130 feet, the slope steepened to about 80 degrees. At about 150-160 feet the dropoff forms a vertical rock wall. This steep escarpment continues down to about 210 feet where a steep sediment talus slope laps up onto the walls forming a sloping bottom of 30-40 degrees. At a depth of 270 feet, this sediment slope with some rock outcrops, decreased to approximately 20 degrees. There was an impression by the divers that the bottom slope increased again farther downslope, but the declivity was not measured.

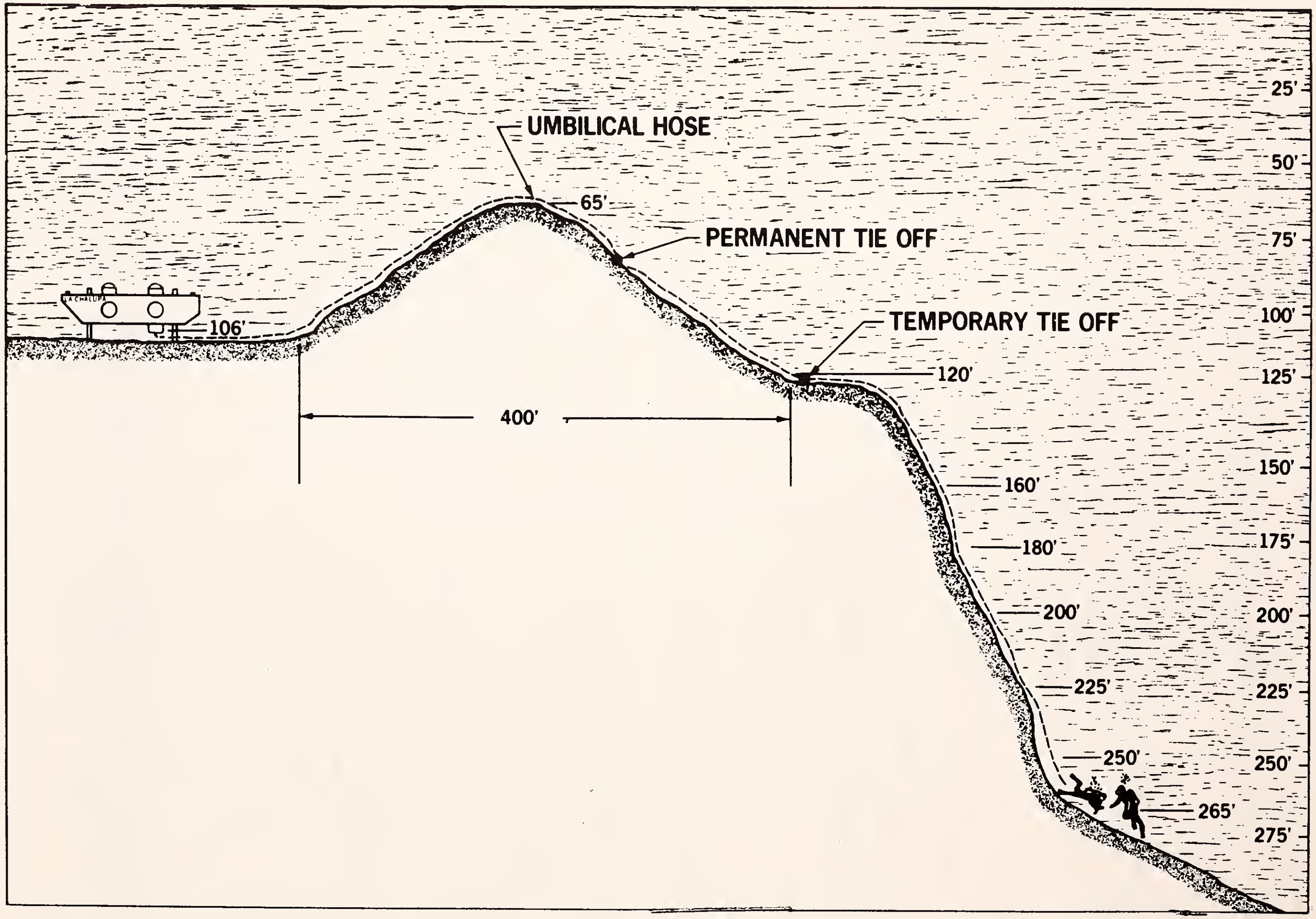

Fig. 18. Topography of PRUNE II dive site.

Diving Procedure:

Two divers made each excursion. Air was supplied via a 700-foot hose (hookah) attached to the habitat and was used for all excursions. A single one-inch hose was used for the first 550 feet. At this point, a "T" valve was inserted so that each diver had an individual 150-foot hose. The divers wore a full-face diving helmet (Kirby Morgan Band Mask, KMB-8) connected to the air hose. The helmet also contained hardwire communication to the habitat. In addition to the hookah, each diver wore a set of double 72-foot^3 scuba tanks as an emergency backup system. These tanks were manifolded so that the air from both tanks could be shunted directly into the diving helmet or breathed through a separate regulator attached to the scuba tanks. When two divers were making an excursion, the other two were in the habitat manning the communication system, logging times, and recording data.

Because of the length of the hookah, approximately 225 feet of it was permanently anchored to the bottom as shown in Fig. 18. Rigid floats and weights were strategically placed along the next 400 feet so that the hose formed a long catenary reaching almost to the surface. This arrangement meant that the divers had only to pull the final 75 feet of hose across the coral-strewn seafloor. Upon reaching the 120-foot depth, the section of hose forming the catenary was hauled down so as to lie flat on the bottom and was tied to a coral head. The divers then had sufficient hose for making the primary descent.

The ascent over the buttress reef while hauling and manipulating the hookah hose required a considerable expenditure of effort by the divers. For this reason, these excursions can readily be classified as working dives. Bottom time began on departure from 120 feet and ended upon leaving the maximum excursion depth.

Testing Procedure:

Three tests were selected to assess the impact of depth and time in the water on psychological performance: an auditory vigilance task (Kennedy 1971), a short-term (immediate) memory task (Digit Span, Wechsler 1955), and a time-estimation task (after Pfaff 1968). The auditory vigilance task was found not to be usable at depth because the exhalation noise from the divers' masks masked the stimulus. Some problems occurred with the administration of the short-term memory test; however, it will be discussed along with the more successfully administered time-estimation test.

The method of time estimation selected for this study was the production method in which the experimenter verbally stated a given interval (standard) and the subject, in the water, was instructed to delimit verbally the beginning and the end of the interval (judgment) that he estimated to be equal to the given standard. For example, the subject in the water would make his estimate by saying "start" at the beginning and "stop" at the end of the estimated interval. A timer located in the habitat used to record the estimate would begin counting at 1/100 sec on the start command and was stopped on

the stop command by the experimenter in the habitat. The standards ranged from a stimulus period of 4 to 24 sec and were randomly ordered. In conducting the digit span test in a fashion similar to Wechsler, the experimenter read sequences of four to ten digits to the diver who then repeated them back on command either in the same or reverse order.

Results:

Ten, two-man excursions were made to depths ranging from 160 to 265 feet. The excursion profiles are shown in Table 33. Because of the required ascent over the buttress reef, the excursion times had to be modified. Table 34 shows the depths of each excursion, the times allowed at each depth without the buttress reef according to the NOAA OPS tables, the modified times taking the buttress reef into account, and the times actually spent at each depth.

While the limits of the NOAA OPS excursion profiles were not tested because of the required ascent over the buttress reef, the feasibility of making deep excursions using air was further demonstrated. Ignoring the problems of handling the long hookah hose, the excursions were uneventful with one exception. On excursion nine, one diver's hookah separated and he was forced to remove his diving helmet and use the backup scuba tanks to return to the habitat from the 120-foot temporary tie-off point shown in Fig. 18.

There were no respiratory problems or symptoms of bends during any of the excursions. One diver experienced light headedness at a depth of 265 feet on an excursion scheduled for 275 feet. The dive was aborted at 265 feet and both divers returned to a depth of 200 feet and completed the excursion. The other diver on this excursion reported no symptoms of narcosis.

The major findings of the time-estimation study were threefold: (1) all subjects made significantly longer time estimates at depth than they did on the surface, (2) this effect was uniform across all time standards, (3) some subjects were more affected than others. Group average estimates for the eight time standards at four pressure levels are illustrated in Fig. 18. Individual performances are shown in Fig. 20. Baseline estimates at surface pressure ranged from 90 to 95% true. All of the estimates made at depth were clearly longer than those made on the surface. Although the underlying cause for this finding is not clear, the trend observed is consistent with results of other studies (Bachrach and Bennett 1973; Baddeley 1975; Thomas, Walsh, Bachrach, and Throne in press) where time estimation was used as a human performance measure in stressful situations.

The results of the digit span test were difficult to interpret since lack of time on many excursions yielded incomplete data for all subjects and learning appeared to occur throughout the mission as shown in Table 35. The variability in responding on the digit span was so great across subjects that statistical evaluation could not be made. One subject did worse at depth (IK), one did better (SK), and the others remained roughly equivalent to surface performance (JM, AW). Though inconclusive, it is interesting to note that some of the divers were able to repeat back a series of up to eight or nine

TABLE 33

Excursion profiles from saturation at 106 fsw

Excursion No.[a]	Maximum depth	Time to 120 ft	Time at 120 ft	Time to maximum depth	Time at maximum depth	Time to 120 ft	Time at 120 ft	Time to habitat
	ft	min	min	min	min	min	min	min
1	160	11	2	1	239	3	5	12
2	180	10	2	1	64	3	2	8
3	180	10	2	1	64	4	1	10
4	200	17	2	10	17	4	2	15
5	200	17	2	2	26	6	1	11
6	225	12	1	3	12	3	1	5
7	225	11	2	2	13	5	1	5
8	250	13	13	4	4	5	2	24
9	250	12	8	10	2	6	2	8
10	265	7	8	5	1[b]	13	4	8

a Two divers each excursion

b Aborted because of nitrogen narcosis in one diver. Both divers ascended to 200 ft and stayed for 8 min.

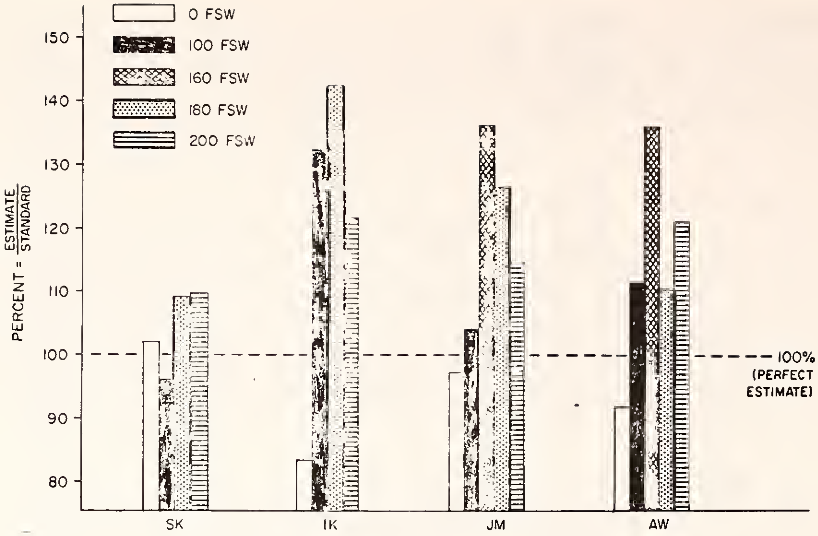

Fig. 19. Average group estimates of eight time standards at four pressures.

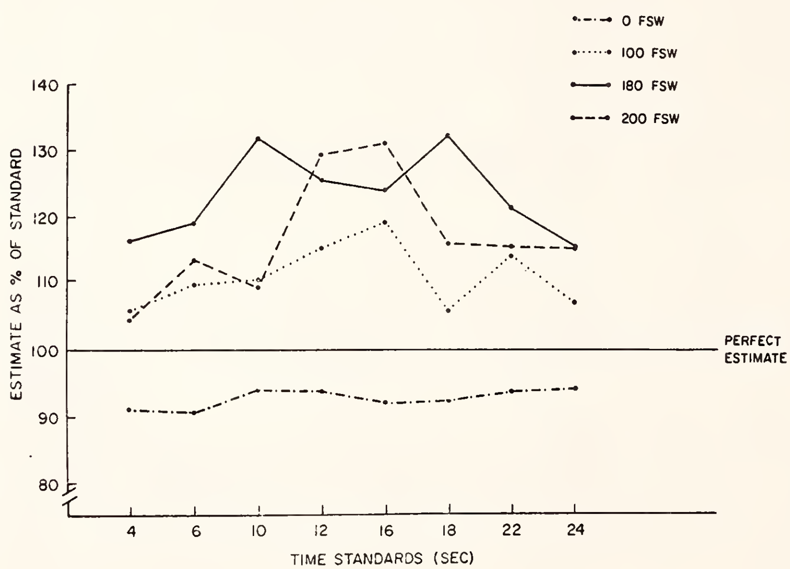

Fig. 20. Individual differences in time-estimation performance at five pressures.

TABLE 34

Comparison of excursion times with and without the buttress reef

Excursion No.	Excursion depth	Time allowed, no buttress	Time allowed, with buttress	Time actually spent at depth
	ft	min	min	min
1	160	360	240	239
2	180	360	65	64
3	180	360	65	64
4	200	262	28	17
5	200	262	28	26
6	225	62	163	12
7	225	62	163	13
8	250	35	9.3	4
9	250	35	9.3	2
10............	265	14.7	5.5	1[a]

[a] One min at 265 ft where excursion was aborted because of narcosis of one diver. Divers stayed for 8 min at 200 ft.

digits at depths down to 200 fsw. Further details of the performance studies may be found in Miller, Bachrach and Walsh (in press).

Conclusions:

PRUNE II further demonstrated the feasibility of using air as a breathing gas to depths of 250 fsw. There was no evidence of pulmonary distress or of decompression sickness. The only problems of a medical nature were ear infections which seem to plague most undersea programs. The shift in time estimation, although statistically significant, is not easily explained. With the exception of the excursion to 265 feet, nitrogen narcosis was not perceived by the divers to be a problem. If narcosis was present at lesser depths, it did not interfere with the execution of the excursions, the tasks required in and around the habitat, or with performance as indicated in the one instance in which a diver had to respond to an emergency situation.

TABLE 35

Raw scores for digit span test obtained at the surface, at storage depth, and during excursions*

Subject	Forward or Backward	Surface	Depth in fsw 106	160	180	200	225	250
IK	F	8	7	--	9	7	--	--
	B	4	7	--	--	--	--	--
JM	F	9	9	9	9	10	--	--
	B	5	6	6	--	--	8	8
AW	F	8	8	8	8	8	--	7
	B	6	6	8	--	--	9	--
SK	F	6	6	6	6	--	8	--
	B	4	5	--	--	--	--	--

* The data represent the number of digits correctly repeated by the subjects at each depth.

V-E SCORE (Scientific Cooperative Operation Research Expedition)

Phase II

Introduction:

While shallow reefs continue to be the focal point for experiments involving manipulation of environmental variables and associated cause-effect relationships, the deeper reefs offer scientists the opportunity to relate the distribution, abundance, diversity, and functional characteristics of the biota to the gradients of parameters associated with rapidly increasing depth.

The few scientific dives made to depths greater than 150 feet have yielded species of coral, algae, and crynoids new to the Bahamas, and some previously reported only from single dredge hauls elsewhere in the world. The deeper dives also revealed information regarding the ability of fish to make large vertical migrations and their tolerance to pressure and associated volume changes involved in such migrations.

The adaptation or lack of adaptation of the photosynthetic components of the ecosystem to the changes in light quality and quantity with depth, and the role of the latter in governing animal behavior are also of great interest. Project SCORE provided marine scientists with the opportunity to study the deep reefs utilizing new diving techniques.

Purpose:

Phase II of SCORE was designed to study the deep reef previously inaccessable to serious scientific investigation and to further verify in the open sea, the vertical excursion decompression profiles tested in the Duke University Laboratory during Phase I of SCORE. This open-sea project brought together for the first time a habitat and a lock-out submersible to aid in the studies. Another technical objective was to test and evaluate a new system for anchoring the submersible Johnson-Sea-Link next to the vertical wall while locking out divers.

Location:	Grand Bahama Island
Date:	April 1 - 27, 1975
Mission Duration:	5 days saturation for each of four teams
Saturation Depth:	60 fsw
Breathing gas:	Habitat - air Excursions - air
Aquanauts:	Four teams of four each

Facilities:

This phase of SCORE utilized Hydro-Lab, the lock-out submersible Johnson-Sea-Link, the support ship R/V Johnson, Sub-Igloo sea-floor station, and two small hemispherical ocean floor safety stations, as well as miscellaneous support boats. These facilities were made available through the cooperative efforts of the National Oceanic and Atmospheric Administration, the Harbor Branch Foundation, and the Perry Foundation Inc. Additional help was obtained from the MacInnis Foundation, Seneca College of Canada, and the Tarrytown Labs Ltd. The arrangement of these facilities on the seafloor is depicted in Fig. 21, which shows the Johnson-Sea-Link anchored next to the reef wall at a depth of 229 feet with a diver locked out and descending to 250 feet (lower right). Other team members are in Sub-Igloo (center) and the Shark Hunter vehicle (center above), while support divers approach Hydro-Lab (upper left). Two underwater safety stations containing air were located along the diver route for decompression stops and emergencies. Surface support vessels are the Undersea Hunter (left) and R/V Johnson.

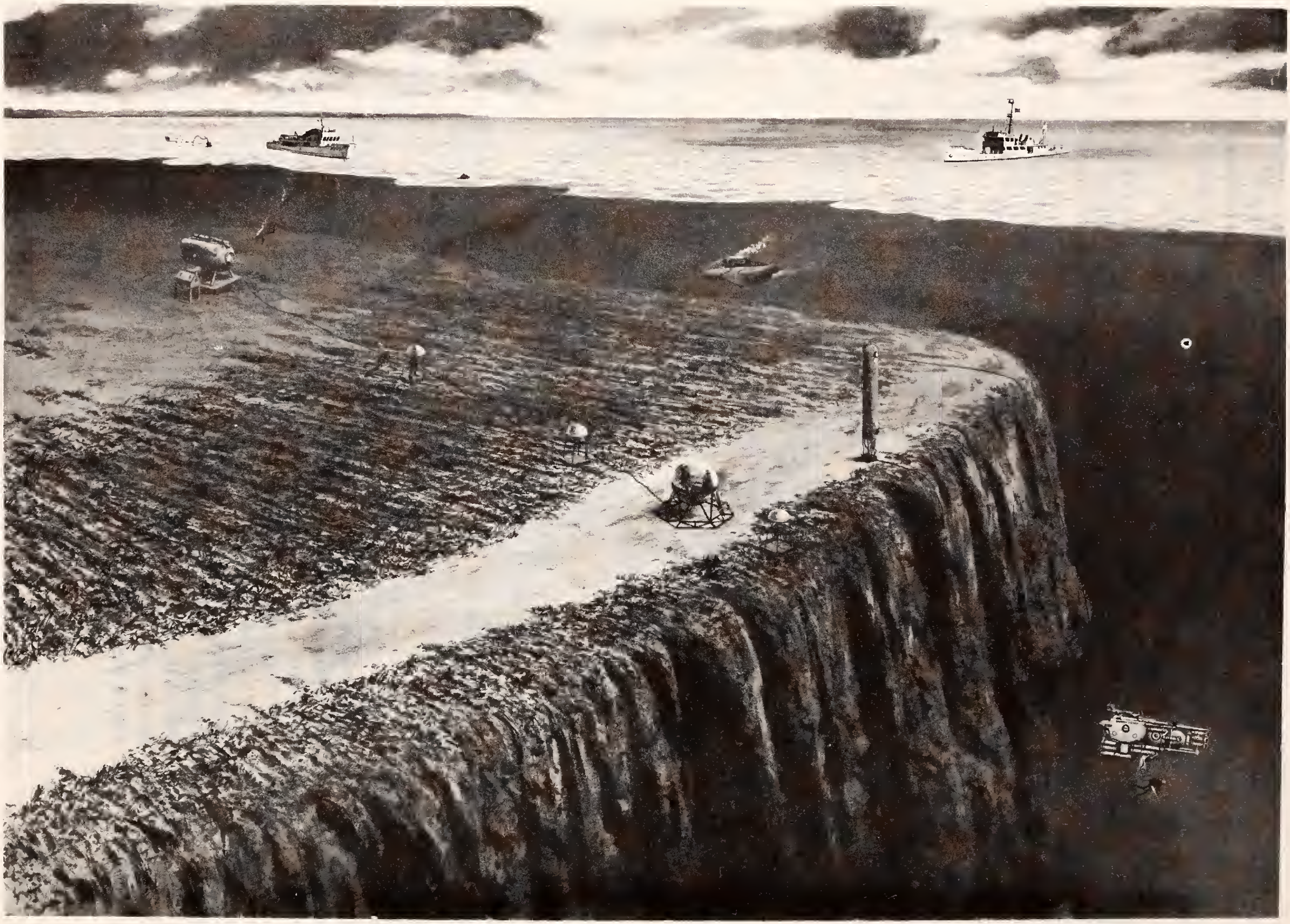

Fig. 21. Artist's conception of project SCORE (Phase II).

The Hydro-Lab habitat was used as the ocean floor saturation facility (see Fig. 5). It is an 8 x 16 foot cylinder maintained at ambient pressure to permit easy access to the sea. The principal life support systems are on an unmanned surface support buoy. For a more detailed description see Section V-B.

Johnson-Sea-Link Submersible

The Johnson-Sea-Link (JSL) is a small research submarine designed to operate at depths to 1,000 feet at speeds up to 1.75 knots (Fig. 22). It has two man-rated pressure hulls: a 66-inch, two-man sphere constructed of four-inch thick acrylic and a separate 59-1/2 inch dive compartment made of welded aluminum. The sphere provides the pilot and one observer with panoramic visibility and is maintained at one atmosphere. The dive compartment has four view ports for scientific observation and is designed as a diver lock-out chamber to 1,000 feet. It is capable of mating to a deck decompression facility. The frame, ballast tanks, gas storage containers, and electrical/electronic housings all are constructed of aluminum. It is equipped with U.Q.C. SONAR, for underwater communication, an FM transceiver for surface communication, an intercom, a Doppler navigation system, a mechanical arm, a life support system (for 5.5 man days) and closed circuit diving equipment.

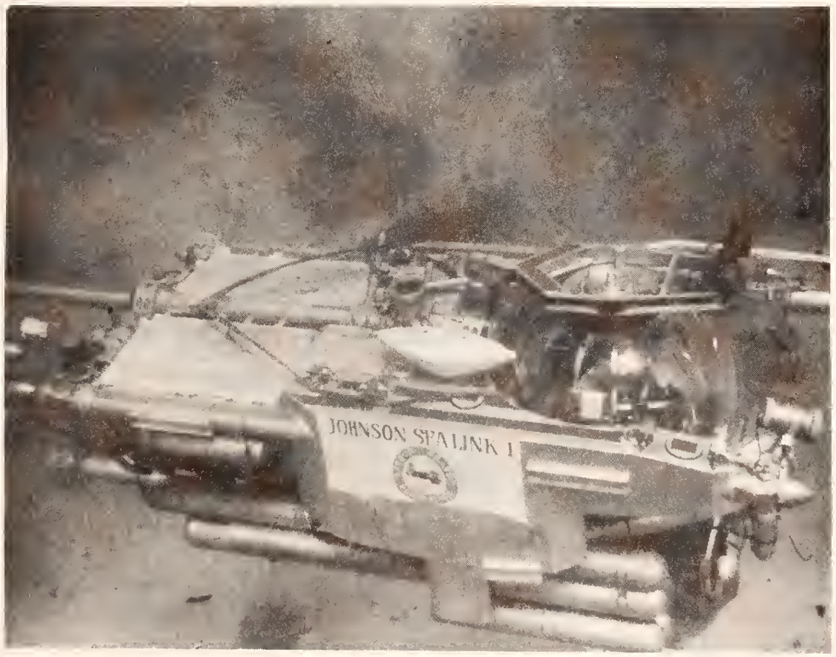

Photo: Mark Benson

Fig. 22. Research submersible Johnson-Sea-Link.

Eight thruster units provide three-dimensional mobility. An oil compensated battery and a static inverter provide power.

Support Vessel R/V. Johnson

Thr R/V Johnson is a 123-foot converted cutter which has been modified extensively for diver support and to handle the Johnson-Sea-Link. It has berthing for 21 persons and is well-equipped with modern radio and navigation systems. An articulated aluminum alloy crane capable of launching and recovering the submersible in seas up to five feet is mounted on the aft deck. A double lock, 350 psi, recompression chamber, capable of mating with the diver lock-out compartment of the Johnson-Sea-Link is located below decks.

Sub-Igloo Sea Floor Station and Underwater Safety Stations

Sub-Igloo is a transparent hemisphere which was used as an emergency sea floor air station and as a diver talking booth. The main structure of the station is a clear, 3/4 inch thick acrylic sphere, eight feet in diameter, formed by joining two hemispheres together with an aluminum ring around the equator. A 39-inch portal has been cut into the lower hemisphere to provide diver entry. An umbilical from Hydro-Lab provided ventilation and communication to Sub-Igloo. The entire structure is made negatively buoyant by suitable ballast in the base. The two acrylic hemispheres shown in Fig. 21 were placed at decompression stops along the path of excursion dives. Ventilation and communication was provided by the umbilical between Hydro-Lab and Sub-Igloo.

Aquanauts:

A total of 16 aquanauts including one female took part in Phase II of SCORE. Their ages ranged from 24 to 46. Each aquanaut received a complete physical examination including long bone x-rays prior to the mission. They all were trained in the use of project equipment and each team included a technician familiar with the lock-out procedures of the submersible.

Excursion Profiles

As a result of the Phase I laboratory study, it was decided not to make excursions to 300 feet during Phase II. It was further decided to keep the 60-minute schedule for the 200-foot excursions, but to limit the 250-foot excursions to 45 minutes as an added safety precaution. Each excursion required decompression prior to returning to the 60-foot habitat depth. The excursion decompression profiles for both 200 and 250 feet are shown in Table 36. One swimming and one submersible lock-out excursion was scheduled each day. A given aquanaut, however, made either a submersible or swimming excursion, never both in a single day.

TABLE 36

Decompression schedules for excursions to 200 and 250 fsw from saturation at 60 fsw

	200 ft Excursion		250 ft Excursion	
Depth (feet)	Ascent Rate (ft/min)	Time (min)	Ascent Rate (ft/min)	Time (min)
250-120	--	--	30	$4\frac{1}{3}$
200-90	30	$3\frac{2}{3}$	--	--
120 stop	--	--	--	$\frac{2}{3}$
120-110	--	--	10	1
110 stop	--	--	--	3
110-100	--	--	10	1
100 stop	--	--	--	7
100-90	--	--	10	1
90 stop	--	$5\frac{1}{3}$	--	6
90-80	10	1	10	1
80 stop	--	4	--	9
80-70	10	1	10	1
70 stop	--	3	--	9
70-60	10	1	10	1
Total		19		45

Procedure:

Two Hundred-Foot Excursions

Two aquanauts, made the five-minute swim, from Hydro-Lab to the edge of the wall using standard, double 72-foot^3 scuba tanks maintaining the 60-foot saturation depth. Upon reaching a depth of 140 feet, approximately 600 feet from Hydro-Lab, they changed to a fresh set of double tanks. They made the

excursion to 200 feet using extra scuba tanks provided as needed. At the end of 60 minutes, they proceeded back to Hydro-Lab, stopping in accordance with the decompression profiles shown in Table 36. The Sub-Igloo and two air stations shown in Fig. 21 were placed at depths of 90, 80, and 70 feet respectively for decompression. The aquanauts were escorted by a small boat containing standby divers during each swimming excursion. Between major excursions the divers were restricted to depths within ±5 feet of saturation depth.

Two Hundred and Fifty-Foot Excursions

Two aquanauts were transported to the 250-foot working site by the Johnson-Sea-Link. The submersible parked on the bottom near Hydro-Lab and the two aquanauts swam over and entered the dive compartment. A submersible technician always accompanied a scientist on each excursion and served as a tender during the dive. After the dive compartment hatch was secured, the sub travelled to the dive site and was attached to the suspended anchor cable at a depth of 229 feet. The pressure in the dive compartment was then equalized to ambient pressure and the hatch opened. The aquanaut exited, and carried out the scientific mission using air supplied by the sub via a 90-foot hookah hose tended by the submersible technician.

Upon completion of the excursion, the aquanaut returned to the submersible. The two aquanauts sealed the hatch and started decompression while returning to Hydro-Lab. Decompression to the 60 fsw storage depth was accomplished in the submersible dive compartment in accordance with the 250-foot schedule shown in Table 36. Should treatment have been necessary following a lock-out excursion, the submersible could return to the surface and mate to the decompression chamber aboard the support ship R/V Johnson. This technique could also be used to transfer a saturated diver to the recompression chamber aboard R/V Johnson in the event of an emergency.

Decompression:

Upon completion of the five-day mission, the aquanauts decompressed inside Hydro-Lab according to the decompression schedule used in Phase I and shown in Table 24.

Hematology and Blood Chemistry

Studies were performed in the same manner as described in SCORE Phase I (Section IV-C) except that red-cells and white-cells were counted visually and sedimentation rate was not measured.

Results:

Each of four teams spent five days on the bottom at the 60-foot saturation depth. With four aquanauts on each team, 80 man-days of saturation were completed. Most of the scheduled excursions were carried out. Those not completed were cancelled due to surface sea conditions preventing the submersible from being launched.

Two Hundred-Foot Excursions

A total of 34 two hundred-foot excursions were made by the four teams. The basic descent and ascent excursion profiles were the same for all excursions. The bottom profiles during the excursions varied, however, depending upon the nature of the marine science mission. Figs. 23 to 26 illustrate the swimming excursion profiles. While all 200-foot excursions were treated as one-hour excursions, it is clear from the figures that the time spent at 200 feet fluctuated considerably. For example, during the 16 excursions represented by Figs. 23 and 24, an average of 40 minutes per excursion was actually spent at 200 feet; whereas in the 18 excursions represented by Figs. 25 and 26, an average of 12 minutes was actually spent at 200 feet. This difference reflects the nature of the marine science missions. In the latter case, the aquanauts were required to collect data over a more extensive vertical depth range. No bends were experienced following any of the excursions. Diving times between excursions were unlimited at storage depth.

An incident worth noting occurred on the first swimming excursion by the first team. Because it was the first excursion, the two divers entered the water near the edge of the wall. The divers were not saturated and both were wearing closed-cycle rebreathers equipped with mouthpieces. A problem developed, the cause of which is unclear, resulting in one of the divers convulsing in the water at a depth of 140 feet on the way down. Following the convulsion, the affected diver was towed back to Sub-Igloo (a distance of about 150 feet) by his buddy diver and by the Operations Director who had been on station in shallower water above the divers. The victim's teeth were clenched shut such that a mouthpiece could not be inserted nor could water enter his mouth.

Upon reaching the Sub-Igloo, the victim was pulled inside (where air was available) and tended by the Operations Director. A second convulsion took place at this point. At the end of about one to one and one-half hours, the victim was conscious, coherent, and was breathing normally. Wearing a helmet, he was then escorted to the dive compartment of the submersible which was now parked next to Sub-Igloo and transferred to the deck decompression chamber on board the R/V Johnson. The attending physician was in the observation compartment of the submersible. Following a five-hour decompression, the victim was flown to Miami, Florida for hospitalization and observation. He was discharged in a few days with no residual effects. A replacement was selected and the remainder of the mission was carried out without further incident. Rebreathers were not used for any other missions since the cause of the accident was not determined.

Two-Hundred and Fifty Foot Excursions

A total of 13 lock-out dives to 250 fsw were successfully completed. Although only one diver made each excursion the tender was also exposed to the hatch depth of 229 fsw. Fig. 27 shows the excursion profile used for the lock-out dives. Because of the nature of the marine science investigations, vertical sections of the reef were traversed ranging in depth from

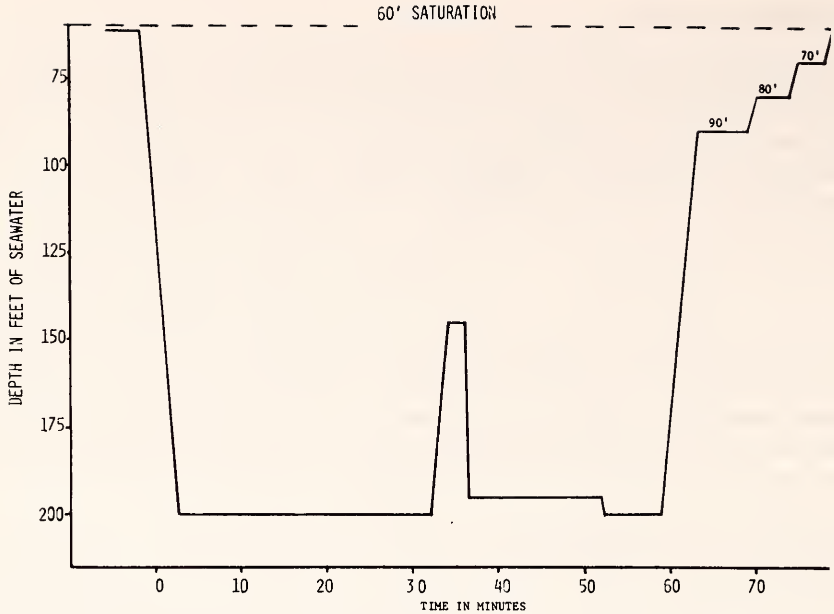

Fig. 23. Swimming excursion profile one--used for eight man-dives.

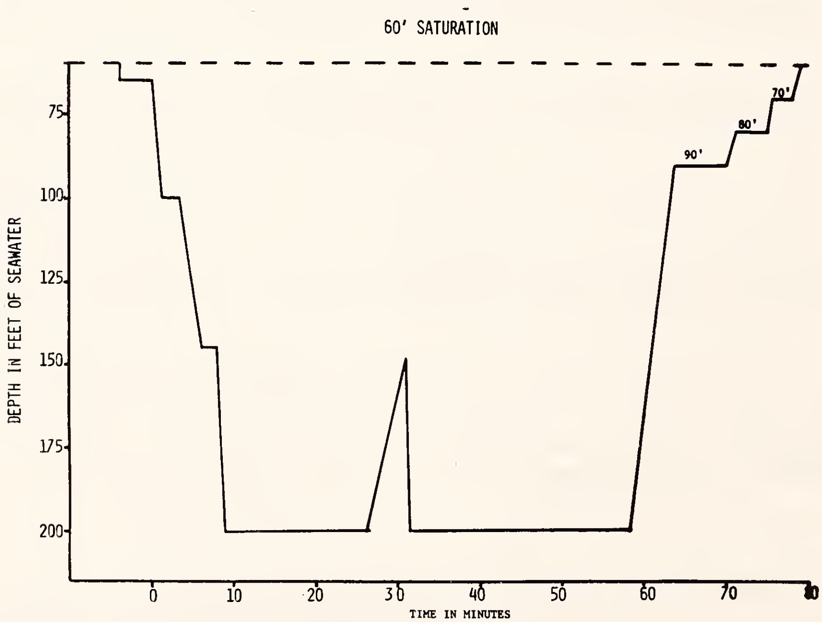

Fig. 24. Swimming excursion profile two--used for eight man-dives.

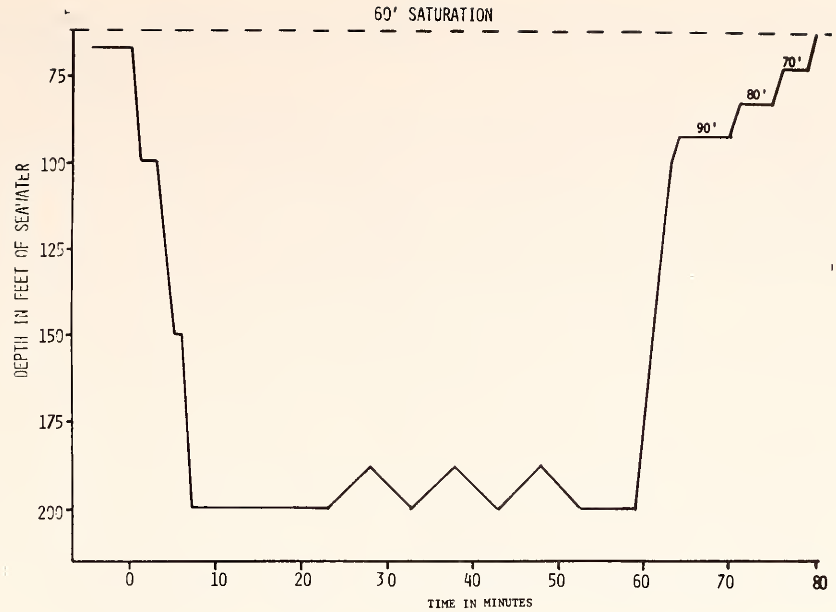

Fig. 25. Swimming excursion profile three--used for eight man-dives.

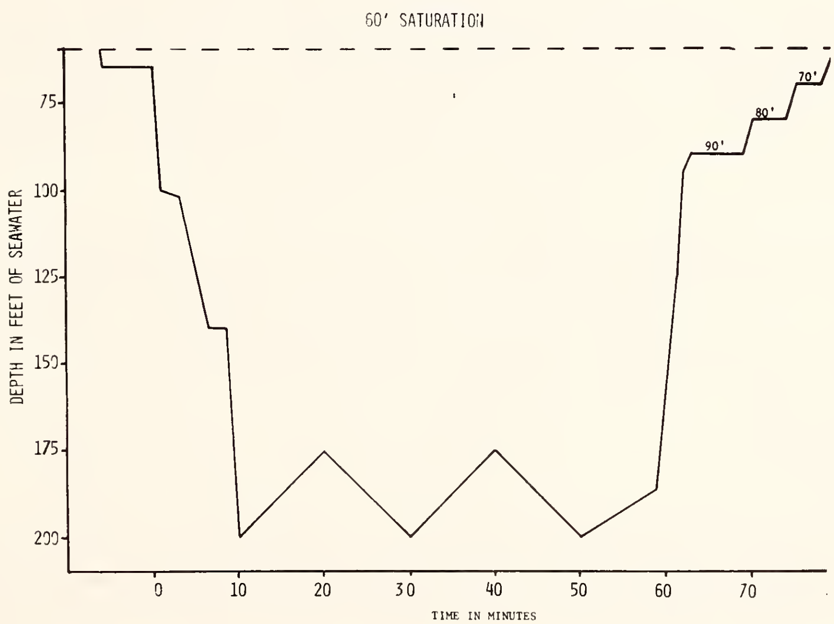

Fig. 26. Swimming excursion profile four--used for ten man-dives.

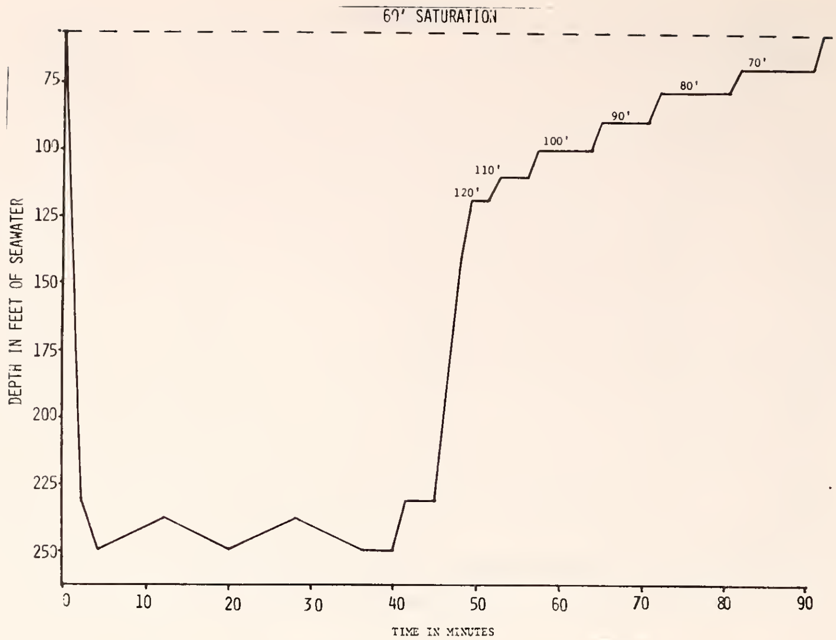

Fig. 27. Excursion profile used for 13 submersible lockout dives.

240 to 250 feet. An excursion usually lasted 36 to 38 minutes between departing from and returning to the hatch depth. The remaining 7-9 minutes of the permissible 45-minute excursion time was used during compression, opening and closing the hatch, storing the air hose and preparing for decompression. No symptoms of bends were experienced during any of the lock-out dives or during decompression back to the 60-foot storage depth.

The divers were observed during the excursions by the submersible pilot and observer from the forward compartment and each dive was recorded on video tape. Several aquanauts reported some subjective feelings of inert gas narcosis. The degree of narcosis varied considerably but none of the aquanauts felt that it interfered with carrying out the tasks at hand.

Biomedical Results:

Medical Data

Many of the divers developed multiple, white pustules of the skin, especially over the back, chest, and upper arms. Bacterial culture of some of these divers showed the presence of *Staphylococcus aureus* consistently.

Subject L.S. developed nausea, vomiting, diarrhea, and fever shortly after decompression from saturation. White-cell count and differential count were suggestive of a bacterial infection and a tentative diagnosis of staphylococcal

enteritis was made. Treatment consisted of intravenous fluids and kaopectate *per os* and recovery was uneventful.

Subject S.E. became nauseated during the first 250-fsw lockout and vomited into the mouthpiece. On returning to the submersible, the subject became limp, experienced blurred vision, and again vomited. Recovery appeared to be complete within two minutes. A similar incident occurred the following day during the 250 fsw lockout and this subject was prohibited, on medical grounds, from further deep excursions and lockouts. No treatment was given other than rest and no further problems were encountered.

Subject J. P. developed otitis media following decompression from saturation and was given tetracycline antibiotics *per os*.

Subject J.H. collapsed shortly after returning to shore following decompression. He recovered sufficiently to walk, with assistance, to the on-site recompression chamber where a 60-fsw treatment table was started. The subject continued to improve during the treatment and consumed several hundred milliliters of fluids consisting of orange drink and water. A tentative diagnosis was made of hypoglycemia and dehydration brought on by abstinence from fluid and food during the nearly 18 hours of decompression. Recovery was uneventful.

Platelet Studies

When the mean percent change in circulating platelet count of the divers was calculated for each sample day there were no statistically significant changes, although there was a trend for counts to be depressed slightly 24 hours post-saturation. When examined individually, four of the divers had reductions in platelet counts greater than 30%. In two of these (38% and 35%), this occurred in the sample collected at saturation depth (60 fsw) after completion of all of the deep excursions and lockout dives.

Subject J.H., who was treated for decompression sickness as a precautionary measure, had a 32% reduction in the post-saturation sample and subject S.E., who experienced difficulty during the lockout dives, had a 31% reduction 24 hours after decompression from saturation depth.

For reasons of logistics it was not possible to obtain control data for platelet aggregation on one team (four subjects) of divers. The remaining six, however, showed a marked and statistically significant reduction in sensitivity of platelets to ADP-induced aggregation in the sample collected during saturation but after completion of the excursion and lockout dives. Evidence of this trend was still present after decompression from saturation depth, becoming variable thereafter. The four remaining subjects showed a trend for aggregating activity to be increased in the post-saturation samples as compared to the ones collected during saturation, suggesting that the activity followed the same pattern as in the other six divers.

Hematology

A slight (13.3% ± 1.49 SEM) but statistically significant ($P < .001$) increase in the mean red-cell count 48 hours post-saturation was the only noteworthy change in red-cells, hemoglobin concentration, or packed-cell volume. No noteworthy changes in plasma enzyme levels occurred.

Platelet Function Studies

In three previous studies of divers using the Hydro-Lab habitat, significant reductions in circulating platelet counts were observed (Philp *et al.* 1974, Philp *et al.* 1975). On these occasions the saturation depth was 42 fsw and a different decompression profile was utilized. In the SCORE open-sea dive there was no statistically significant loss of platelets. By contrast, reductions in platelet counts were marked and highly significant in the Duke SCORE Phase I experiments. These data indicate a relationship between the risk factor for decompression sickness and the loss of platelets and further suggest that the SCORE open-sea excursion profile was the less hazardous of the two. Platelet aggregating activity, however, was depressed by the same order of magnitude in both situations.

The possibility that the higher O_2 exposures encountered in the SCORE Phase I experiment might have been a contributing factor to the platelet loss cannot be discounted. However, the fact that a marked and significant loss of platelets occurred following the 250-fsw bounce dive, a dive which was associated with a 100% incidence of skin bends (pruitis) but which had a bottom time of only 13 min. would argue that decompression stress (i.e. bubble formation) is the primary causal agent. Further details are discussed in Philp, Freeman, and Francey (1975).

<u>Summary</u>:

Phase II of SCORE clearly demonstrated the feasibility of conducting open-sea working decompression excursion dives on air to depths up to 250 feet from an air saturation storage depth of 60 fsw. The open-sea program further verified the excursion decompression schedules tested in the Phase I laboratory program. If inert gas narcosis was present, it was not, in the opinion of aquanauts or observers, of sufficient magnitude to impair cognitive or psychomotor performance. The program also demonstrated the viability of combining habitat and submersible operations into a cohesive scientific effort.

VI <u>GENERAL CONCLUSIONS</u>

A number of general conclusions can be drawn, based on the analytical work, laboratory tests and field operations described in this report.

1. The use of gas-loading analysis of previous diving experience affords an excellent starting point for computation of new decompression procedures.

This approach has led to a matrix of limiting values (the NOAA OPS matrix) which has been used for computation of many of the decompression procedures reported here.

2. Evidence, to date, shows that saturated divers can work safely while breathing air at depths greater than those at which they could operate with equal safety from sea level. The extra depth, based on subjective impressions, is approximately equal to that of the habitat. This accommodation to the higher nitrogen environment becomes effective in about one day, and reaches a maximum in two-to-three days.

3. Descending no-decompression air-excursion dives with depth changes up to 180 fsw have been made in the laboratory from saturation at depths to 120 fsw in a normoxic nitrogen atmosphere.

4. Air-excursions to depths of 250 fsw with bottom times up to one hour can be safely conducted from saturation at 60 fsw with appropriate decompression stops.

5. Air-excursions to 300 fsw from air-saturation at 60 fsw are unsafe due to the possibility of oxygen toxicity.

6. The practical limit for excursions with saturation normoxic mixtures has not been established but is not likely to be greater than 300 fsw.

7. Ascending air-excursions with operationally useful times and depths can be made safely from a nitrogen/oxygen storage mixture. Such excursions, however, are limited to about 60 fsw above saturation depth.

8. The risk of nitrogen narcosis is still a considerable problem at deeper depths and it is recommended that divers be selected for minimal sensitivity. An oxygen toxicity sensitivity test would also be advisable.

9. Only the most highly trained, competent and balanced individuals should be permitted to make excursions to 250 fsw and then only after thorough training on the equipment to be used and the tasks to be accomplished. No reliance should be placed on individual divers' comments as to their ability to function at such depths.

10. Efficient decompression from nitrogen/oxygen saturation can be accomplished without breathing pure oxygen by mask.

11. The occurance of oxygen toxicity symptoms during bends treatment (SHAD II) suggests that an alteration occurs in some saturated divers that precludes their ability to accommodate to what would normally be a routine treatment procedure with 100% oxygen.

12. There is a point, apparently, in the range 0.5 to 0.6 atm oxygen partial pressure, where a change in red-cell production occurs but which is too low to invoke symptoms of oxygen toxicity. This adaptive process

can continue for many weeks and can result in severe debilitation on return to sea level conditions.

13. A post-dive reduction in circulating platelet count following air-saturation has been confirmed.

14. Based on available evidence, air-saturation should not be conducted at depths beyond 60 fsw.

15. Evidence currently available indicates that normoxic nitrogen/oxygen saturation exposures can be conducted to depths of 120 fsw. The limit for such exposures, however, has not been established.

VII APPLICATIONS OF SHALLOW HABITAT AIR DIVING

The operational programs which have been conducted thus far, serve not only as steps in a broad development program, but also serve as outstanding examples of the applicability of shallow habitat excursion diving. For example, the SCORE operation which used decompression excursions, particularly showed that excursions can give scientists convenient access to greater depths more efficiently and for longer periods than had been possible previously. Scientific observations and experiments, resource survey and management, pollution analysis, archaeology and commercial harvesting, all are examples of missions which can be aided by the use of shallow excursion techniques.

The recent expansion of the off-shore industry similarly offers various possibilities of using shallow excursion techniques. While many tasks require deep diving, there still is much work at depths less than 250 feet. The laying of pipeline in this depth range is but one of the possible types of jobs.

These and other potential applications depend, as do many areas of technology, on trade-offs. To evaluate these techniques properly they must be compared with other options. The basic purpose of the programs described in this report were to reach open-sea work areas using vertical excursions from shallow saturation depths with air as the excursion breathing gas, and nitrogen as the sole inert gas. The traditional methods, by comparison, include surface diving (with air or "mixed gas," e.g., helium-oxygen), and saturation without vertical excursions, (e.g., air or mixed gas saturation) at approximately the working depth.

The shallow excursion technique permits longer work periods in the air diving domain, and because of accommodation to narcosis, it permits the use of air to be extended into the shallow end of the mixed-gas or helium domain. At the other end of the continuum, we have seen that relatively shallow working dives can benefit from air-saturation. For example, the US Navy Diving Tables allow a 30-minute no-decompression dive at 90 feet, whereas a diver can spend a six-hour no-decompression excursion to this depth from an air saturation at 42 feet. To achieve approximately the same working time, using

USN Standard Air Decompression Tables, a diver would need to make three dives and three decompressions totalling about five hours and ten minutes. At 150 feet, one hour of work costs about two hours of decompression time (using US Navy tables). Using helium (mixed-gas), the depth can be extended, such that at 250 fsw an hour of work may cost three hours of decompression, and two hours' work requires nearly four hours of decompression.

In contrast, from a saturation depth of 85 fsw a diver can make a six-hour excursion to 150 feet and return to the habitat with no decompression stops.

Another factor to be considered is gas cost. For example, four hours of work at 250 fsw breathing a helium-oxygen mixture open circuit will require on the order of $200 worth of gas, more than ten times the cost of air. Thus the cost trade-offs depend on depth, work required, equipment availability and the cost of gas. A typical job requiring four to six hours per day, for several days, of work at 250 feet would clearly be more cost-effective using shallow habitat excursions.

Existing closed-circuit equipment which works but which has not reached commercial acceptability due to complexity, reliability, and cost would permit the four-hour dive just mentioned to be performed with nominal cost for gas. Rebreathers have proven to be effective in scientific diving and will eventually be used more extensively by the working diver, although at the present time are very expensive. Another cost factor demonstrated in SCORE, SHAD II, and especially in the Hydro-Lab program is the use of an air-based habitat to depths of 60 fsw. When air is used as the storage gas, it can be easily vented, thus avoiding the cost of recirculating scrubbers and CO_2 absorbent chemicals. Although it is cheaper by far and more available than helium, the cost of nitrogen must be considered in all but the shallowest air operations.

The usefulness of the air-excursion technique is not limited to diving. Caisson and tunnel work may prove to be just as profitable an application. This suggestion was made several years ago by Behnke (1968) and again by personal communication in 1974. As Behnke points out "The urgent requirement for Metropolitan rapid transit and conduits for waste disposal, power lines, etc. will necessitate large-scale subterranean (and subaqueous) pressurized tunneling. Current work in compressed air is not only prohibitive in cost but incurs as well decompression hazards, notably bone necrosis. The pressurized Habitat and excursion principle should eliminate current decompression problems ...The pressurized Habitat should permit greatly augmented work-time attended by minimal decompression and elimination of decompression hazards."

While tunnel workers would not be expected to spend long periods (one to two weeks) under pressure, a work schedule involving saturation of three to four days at depths of 30 to 40 fsw followed by a single decompression to the surface is certainly within the realm of practicality. At the present time, tunnel workers can spend two 45-minute periods each day at a depth of 112 feet with each period requiring a decompression of about 28 minutes.

By contrast, using the nitrogen/oxygen excursion tables, these same men could work for four hours at a depth of 100 fsw and return to a storage depth of 40 fsw with no decompression required. If such a work schedule were carried out for four days, the total work time per man would be 16 hours if only one such shift per day were done. This compares to seven and one-half hours a week using two 45-minute work periods. At the end of four days a single decompression of about 11 hours from the 40 fsw saturation depth would be required. Thus, over twice the amount of work would be achieved and only one decompression, instead of the ten now required during a typical five-day period.

Many variations on such a schedule could be made depending upon the required working depths. In addition to the increased work output, the significant reduction in the number of decompressions should benefit the workers by reducing the immediate incidence of bends and the long term incidence of osteonecrosis. Concomitantly, insurance costs should go down because of the added safety margin.

From an engineering standpoint, all that would be needed would be some type of compartmentation in the operational pressurized tube.

VIII FUTURE REQUIREMENTS

The shallow habitat excursion and subsequent field operations, culminating in 1975 with the SCORE project have demonstrated new techniques of diving. This is just a start, however, and much more investigation is needed to give the underwater scientist, engineer, explorer and worker added working time and safety. Further studies should include the development of:

1. Longer decompression excursion times from both air and normoxic nitrogen habitats.

2. Repetitive decompression excursion procedures, in which excursions can be computed taking into account previous excursions and habitat intervals.

3. Additional emergency surfacing procedures from saturation for depths in excess of 50 fsw.

4. An updated NOAA OPS matrix which includes experience gained since 1972.

5. New excursion procedures for use from an air or nitrogen habitat in which helium/oxygen is used as the breathing mixture.

6. Appropriate decompression procedures for the excursions mentioned in #5.

7. Maximum practical limits in such areas as:

a. Time-depth profile for air saturation exposures taking into account oxygen toxicity

b. time-depth profile for excursions on air

c. saturation depth for normoxic (or other non-air) nitrogen habitat environments

d. depth at which adaptation to nitrogen narcosis permits safe diving, both for air and nitrogen/oxygen mixtures

8. Treatment tables for use when oxygen toxicity is present. Such tables must consider the accumulated oxygen exposure and developing toxicity.

9. Finally, there is a need for further study of the phenomenon of "adaptation" to nitrogen narcosis. "Adaptation," as a result of nitrogen saturation has been observed in laboratories and at sea (NOAA OPS, TONOFOND, and PRUNE), both subjectively and with objective evidence. On the other hand, the SCORE experiment at Duke University failed to reveal meaningful changes. Practical understanding of this phenomenon is of critical importance to the entire concept of nitrogen excursion diving.

Bachrach, A. J., and P. B. Bennett. 1973. The high pressure nervous syndrome during human deep saturation and excursion diving. Forsvars-medicin. 9(3): 490-495.

Baddeley, A. 1975. Memory in depth. New Scientist. 13 February.

Beckman, E. L., and E. M. Smith. 1972. Tektite II, Medical supervision of the scientists in the sea. Texas Reports, Biol. Med. 30(3):1-204. Galveston, Texas.

Behnke, A. R. 1968. Medical aspects of work in pressurized tunnel operations. Transit Insurance Administrators, San Francisco, Calif. Pages 50-51.

Behnke, A. R. 1969. Early decompression studies. In P. B. Bennett and D. H. Elliott, eds. Physiology and medicine of diving and compressed air work. Williams and Wilkins, Baltimore.

Behnke, A. R. 1975. Personal communication.

Bond, G. F. 1964. New developments in high pressure living. U.S. Navy Submarine Medical Research Laboratory, Report No. 442. Groton, Conn.

Bond, G. F. 1970. Man's role on the ocean floor. Phys. Med. Biol. 15:186.

Clark, J. M. and C. J. Lambertsen. 1971. Pulmonary oxygen toxicity: a review. Pharm. Rev. 23:37-133.

DeLara, A. 1975. Commandante Medico de la Armada Espanol, Centro de Buceo de la Armada, La Algameca, Cartagena, Spain. Personal communication.

Edel, P. O. 1970. Experiments to determine decompression tables for the Tektite II 100 fsw mission. NASA contract no. 14-01-0001-1384. J&J Marine Diving Co., Houston, Texas.

Edel, P. O. 1970. Surface interval providing safety against decompression sickness in hyperbaric-hypobaric exposures. Final report on contract NAS 9-9036. J&J Marine Diving Co., Houston, Texas.

English, J. G. 1973. LORA-1 Dive Report - saturation dive no. 1. Memorial University of Newfoundland, St Johns, Newfoundland, Canada.

Hamilton, R. W., Jr., J. B. MacInnis, A. D. Noble, and H. R. Schreiner. 1966. Saturation diving at 650 feet. Tech. Memo. B-411. Ocean Systems, Inc., Tonawanda, N.Y.

Hamilton, R. W., D. J. Kenyon, M. Freitag, and H. R. Schreiner. 1973. NOAA OPS I and II. Formulation of excursion procedures for shallow undersea habitats. Tech. Memo. UCRI No. 731, July. Union Carbide Corporation, Tarrytown, N.Y.

Kennedy, R. S. 1971. A comparison of performance on visual and auditory monitoring tasks. Hum. Factors. 13:93-97.

Kinney, J. S., S. M. Luria, M. S. Strauss, C. L. McKay, and H. M. Paulson. 1974. The effects on visual performance and physiology in shallow habitat air dives series (SHAD I and II). Report No. 793. Naval Submarine Medical Research Laboratory, Groton, Conn.

Kinney, J. S., S. M. Luria, and M. S. Strauss. 1974. Visual evoked responses and EEG's during shallow saturation diving. Aerosp. Med. 45:1017-1025.

Lambertsen, C. J. and W. B. Wright, eds. 1973. Multiday exposure of men to high nitrogen pressure and increased airway resistance at natural inspired oxygen tension. Aerosp. Med. 44(7):821-869.

Langley, T. D. 1973. Neurophysiological investigation of inert gas effects. Ocean Systems Inc. ONR contract N00014-69-C-0405. Tarrytown, N.Y.

Langley, T. D., and R. W. Hamilton, Jr. 1975. Somatic-evoked brain responses as indicators of adaptation to nitrogen narcosis. Aviation, Space and Environ. Med. 46(2):147-151.

Larsen, R. T., and W. F. Mazzone. 1967. Excursion diving from saturation exposures at depth. Pages 241-254. In C. J. Lambertsen, ed. Proceedings of the third symposium on underwater physiology. Williams and Wilkins, Baltimore.

Miller, J. W., J. G. Vanderwalker, and R. A. Waller. 1971. Scientists-in-the sea, Tektite II. U.S. Department of the Interior, Wash., D.C.

Miller, J. W., A. J. Bachrach, and J. M. Walsh. 1976. Assessment of vertical excursions and open-sea psychological performance at depths to 250 fsw (in press).

Moeller, G. 1974. Human factors studies of hydrospace systems presented at the AIAA life sciences and systems conference, Arlington, Texas.

National Oceanic and Atmospheric Administration (NOAA) 1975. Diving manual --- diving for science and technology. U.S. Government Printing Office, Stock No. 003-017-00283, Wash., D.C.

Pauli, D.C. and H. A. Cole, eds. 1970. Project Tektite I. ONR Report DR-153, Office of Naval Research, Department of the Navy, Arlington, Va.

Pfaff, D. 1968. Effects of temperature and time of day on time judgements. J. Exp. Psychol. 76(3):419-422.

Philp, R. B., D. Freeman, I. Francey, and K. Ackles. 1974. Changes in platelet function and other blood parameters following a shallow open-sea saturation dive. Aerosp. Med. 73-76.

Philp, R. B., D. Freeman, I. Francey, and B. Bishop. 1975. Hematology and blood chemistry in saturation diving: I. Antiplatelet drugs, aspirin and VK 744. Undersea Biomed. Res. 2(4):233-249.

Philp, R. B., D. Freeman, and I. Francey. 1975. Hematology and blood chemistry in saturation diving II. Open-sea vs. hyperbaric chamber. Undersea Biomed. Res. 2(4):251-265.

Schaefer, K. E., and J. H. Dougherty. 1976. Nitrogen bursts in the expired air during oxygen breathing in decompression from air dives: a sign of bubble resolution. Naval Submarine Medical Research Laboratory, Report No. 826. Groton, Conn.

Schmidt, T., G. Moeller, R. Hamilton, and C. Chattin. 1974. Cognitive and psychomotor performance during NOAA OPS I and II. Tech. Memo. CRL-T-799. Union Carbide Corporation, Tarrytown, N.Y.

Schreiner, H. R., and P. L. Kelley. 1971. A pragmatic view of decompression. In C. J. Lambertsen, ed. Underwater physiology, proceedings of the fourth symposium. Academic Press, N.Y.

Thomas, J. R., J. M. Walsh, A. J. Bachrach, and D. R. Thorne. (in press.) Differential behavioral effects of nitrogen, helium, and neon at increased pressures. In C. J. Lambertsen, ed. Proceedings of the fifth symposium on underwater physiology. Federation of American Societies for Experimental Biology, Bethesda, MD.

Valeri, C. R., H. Feingold, C. G. Zaroulis, R. L. Spahr and G. M. Adams. 1974. Effects of hyperbaric exposure on human platelets. Aerosp. Med. 45(6): 610-616.

Wechsler, D. 1955. Wechsler adult intelligence scale. Psychological Corporation, New York.

Widell, P. J., P. B. Bennett, P. Kivlin, and W. Gray. 1974. Pulmonary oxygen toxicity in man at two ata with intermittent air breathing. Aerosp. Med. 45:407-410.

Workman, R. D., G. F. Bond, and W. F. Mazzone. 1962. Prolonged exposure of animals to pressurized normal and synthetic atmospheres. Naval Submarine Medical Research Laboratory. Rpt. No. 374, Groton, Conn.

Workman, R. D. 1965. Calculation of decompression schedules for nitrogen-oxygen and helium-oxygen dives. Research report no. 6-65. U.S. Navy Experimental Diving Unit, Wash., D.C.

U.S. GOVERNMENT PRINTING OFFICE: 1976-210-801/366